DISCRIMINATION OF CHANGES IN COMPLEX AUDITORY STIMULI

By

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I dedicate this dissertation to my teachers... past, present, and future.

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Four studies explored how listeners process complex auditory information. In Experiment 1, the effect of signal frequency uncertainty on the detectability of a tone was investigated. Listeners' thresholds for the detection of a signal in a broadband noise masker and in a multitone (profile) masker were measured. The results indicated that, for both masker conditions, uncertainty about signal frequency hindered detection. In Experiment 2, the effect of masker uncertainty on the detection of amplitude modulation was explored. Detection for two rates of amplitude modulation, 10 and 100 Hz, was compared. The 100-Hz modulation rate was more susceptible to masker uncertainty than the 10-Hz modulation rate. In Experiment 3, the ability to detect signal envelope fluctuations was measured when a masker with a fluctuating

envelope was presented simultaneously. Signal envelope detection was poorer with the masker present, despite the fact that the signal and masker were separated in frequency by 2 octaves. This interference occurred for signal and masker envelope fluctuation rates up to 160 Hz, and for maskers with envelope fluctuation rates up to twice the rate of the signal. In Experiment 4, discrimination of changes in amplitude-modulation rate was explored. Four carrier frequencies were compared. The frequency of the carrier had little or no effect on rate discrimination. The spectral cue available to the listener was also varied. From those conditions, it appeared that the most likely discrimination cue was a comparison between the absolute frequencies of the sidebands. Under certain conditions, pitch, too, could be used as a cue. The effect of modulation depth on rate discrimination ability was also measured and performance was found to deteriorate as the depth of modulation was reduced.

These studies provide support for the more recent view of signal detection that describes it in terms of simultaneous, across-frequency comparisons. Results indicate that listeners are able to monitor frequency information across the spectrum, and that additional, irrelevant frequency information can be detrimental to signal detection. The results are also considered in terms of spectral and temporal modes of processing.

CHAPTER 1

INTRODUCTION

Historical Perspective

G. von Bekesy (1960), in his classic experiments, showed that each point along the basilar membrane vibrates with a frequency equal to the frequency of the input sinusoid. He also showed that the amplitude of the vibration at each point varies with the frequency of the input, and at some place along the basilar membrane a maximum vibration occurs. Thus the point of maximum vibration also varies with the frequency of the input tone. For higher frequencies the maximum vibration occurs near the base of the basilar membrane and moves nearer the apex for lower frequencies. Thus, one can view the cochlear excitation process as a distributed (spatial) filter.

Egan and Hake (1950), Fletcher (1940), and Wegel and Lane (1924) have interpreted pure-tone masking data as evidence that the peripheral auditory system can be modeled as a set of filters or a series of resonant systems. Each of the filters appears to respond selectively to a narrow range of frequencies, while attenuating those frequencies outside this critical range.

Fletcher (1940) referred to this region as a "critical band."

Fletcher (1940) and a later replication (Swets, Green and Tanner, 1962) determined the effect of bandwidth on the detection of a sinusoidal signal located in the center of a noise-band masker. In all bandwidth conditions, the noise-power density, N_o, was held constant. The data suggested that for large bandwidths of a noise the detectability of the signal was essentially constant and independent of bandwidth. For example, the amount of masking produced by two noises, having bandwidths of 10,000 Hz and 90 Hz and differing in power by approximately 20 dB, was about the same. It was as if the energy at frequencies outside the critical band were ignored by the detection process. These results demonstrated that noise energy outside the critical band had little effect on the detectability of the signal within the critical band.

Fletcher also found that as the noise band was reduced to within a certain width, the signal became easier to detect. The bandwidth of the noise where the detectability of the signal changed was referred to as the critical band. Fletcher measured critical bands for several signal frequencies. He found that the width of the critical band varied as a function of the signal frequency. Subsequent to Fletcher's work, a variety of techniques have been used to estimate the width of the

critical band region. Critical band width estimations have varied across techniques. All estimates agree, though, that the width of the critical band is approximately a constant proportion of the frequency centered within the band. The exact proportion value varies from 0.07 to 0.15, depending on the experimental technique. The approximate width of the critical band is about 0.1 times the center frequency. Thus, the estimated width of the critical band at 1000 Hz is 100 Hz.

Broadband Auditory Processing

The energy within the critical band has been the focus of theory in the traditional masking experiments. Specifically, the ratio of signal energy to noise energy was considered to be the critical quantity. One idea proposed that the signal is just detectable when the signal power is equal to the noise power in a critical band (see Eq. 1.1). Zwicker, Flottorp and Stevens (1957) called this hypothesis the critical ratio hypothesis. According to the critical ratio hypothesis,

$$S_P = N_O W, \tag{1.1}$$

where S_P is the power of a signal that is just detectable in the noise (i.e., masked threshold), N_O is the noise-power density, and W is the bandwidth of the noise. The quantity N_O times W is the total noise power in the critical band. Therefore, when a signal is added

to the noise the power in the critical band is doubled. In the typical two-alternative, forced-choice task the signal interval can be identified by the elevated power in that critical band containing the signal. Recently, several lines of research have shown that energy located outside the critical band of a signal may contribute to its detection.

Profile Analysis

Green and his colleagues have proposed a detection strategy (Green, 1988) referred to as "profile analysis." Results from a series of studies have shown that spectral information outside a signal's critical band may facilitate its detection. The basis of this type of detection is a simultaneous comparison across two or more critical bands within a single-trial interval.

In a typical experiment, listeners are asked to detect an increase in the intensity of one component of a multicomponent waveform. This multicomponent waveform generally consists of 21 sinusoids that range in frequency from 200 to 5000 Hz and are equally spaced on a logarithmic frequency scale. The spacing of these components is such that there is no more than one component per critical band.

A two-alternative, forced-choice (2AFC) task is used. On each stimulus presentation, the overall level of the stimulus is randomly chosen from a 20-dB range. The

median level of the intensity range is typically 60-dB. Randomizing the overall level reduces the possibility of listeners using the absolute level in one critical band as a cue for detection of the signal.

The profile studies have shown that the detection of an intensity increment in a single component is improved as the number of components of a multicomponent waveform is increased (Green, Kidd, and Picardi, 1983; Green, Mason, and Kidd, 1984). Listeners' thresholds are approximately 10 dB better in the 11-component condition than in the 3-component condition. These results suggest that energy in frequency regions remote from the signal frequency may facilitate the detection of the signal. Green (1988) has suggested that when remote frequency information is available, the crucial comparison is a simultaneous one across different critical bands.

Comodulation Masking Release

A different line of research has also demonstrated that simultaneous, across-frequency comparisons may be advantageous in signal detections tasks. Hall, Haggard, and Fernandes (1984) compared listeners' abilities to detect a 1000-Hz tone in two different noise conditions. In one condition, random noise was used. The envelope fluctuations of the random noise in different critical bands were essentially independent. Coherent noise was used in the other condition. It was generated by

multiplying a wideband noise by a 50-Hz low-pass noise. The fluctuations of the noise in this condition were similar across the various frequency bands, that is, the different noise envelopes were correlated or coherent.

Hall et al. (1984) determined signal thresholds as a function of bandwidth for both the random and coherent noises. For both conditions, signal thresholds increased as the noise bandwidths were increased up to a critical band. In the random noise condition, thresholds remained constant when the bandwidth of the noise exceeded a critical band as it did in Fletcher's original experiment. For the coherent noise condition, when the noise bandwidth exceeded a critical band, signal thresholds decreased. This result suggested that the across-frequency envelope coherence reduced the amount of masking due to the noise. This finding has been termed comodulation masking release or CMR. Additional studies of the CMR effect have also been published by Buus (1985), Cohen and Schubert (1987a, 1987b), Hall (1986), McFadden (1986, 1987).

Recent Signal-in-Noise Study

Gilkey (1987) extended the previous work on the detection of a signal in noise using a stimulus presentation level that was randomized over a 30 dB range. With the presentation level randomized over such a large range, a comparison of the energy level outputs of a critical band across trial intervals would not be a

reliable cue for the detection of the signal. Signal thresholds, for both fixed and random stimulus presentation levels, revealed that the randomization of presentation level had a greater effect on the narrowband condition than on the wideband condition. The additional spectral information in the wideband condition enabled listeners to detect the signal almost equally well whether the level was fixed or random.

In addition, Gilkey looked separately at the effect of randomizing the stimulus level as a function of masker bandwidth and as a function of masker duration. As either bandwidth or duration was increased, a reduction in masking was observed. The results are consistent with the findings of Green and Hall that listeners are able to use frequency or temporal information located outside a signal's critical band in a simultaneous detection process.

Auditory Processing Strategy

Two views of how listeners detect the presence of a signal within a complex waveform have been presented. The important aspect of signal detection, according to the traditional view, was the energy within the signal's critical band. It was believed that energy outside this frequency region did not influence detection and was essentially ignored. Signal detection in a two AFC task would be carried out as follows. In interval one, the

acoustic energy within the narrow region around the signal frequency would be computed and stored in a short-term memory. In interval two, a second energy computation would be made regarding the same frequency region. These two computations would then be compared and the one with the greater amount of energy would be selected as the signal. The important comparison, then, is the successive, across-interval comparison of the energy levels within a single critical band centered at the signal frequency.

A more recent view of signal detection in complex waveforms has been proposed and is based on the findings of the CMR and profile analysis experiments. One important difference between the more recent view and the traditional view is the role of energy outside the signal's critical band. Energy that is remote from the signal frequency is believed to influence the decision about whether a signal is present or absent, according to the more recent view. Signal detection in a two AFC task would be carried out as follows. In interval one, a simultaneous comparison across critical bands would be made. A decision would then be made, based on this across-frequency comparison, as to whether the signal was present or absent. In interval two, a second simultaneous comparison and decision would be made. Finally, the two decisions from interval one and two would be compared successively. This successive comparison does not provide

much information about the signal's occurrence in terms of absolute energy because the overall level of the sounds is randomly determined for each interval. The important comparison is the simultaneous, within-interval comparison of energy levels across critical bands.

Overview of Dissertation Studies

The purpose of the studies presented in this dissertation was to further the investigation of auditory processing of complex stimuli. The first study, which will be discussed in Chapter 2, was undertaken with these two views of auditory processing in mind. Listeners in the experiment were asked to detect a signal whose frequency was randomly determined on each trial.

The two views might make different predictions regarding the effects of signal frequency uncertainty. If the listener was relying on a computation of the energy within the signal's critical band, frequency uncertainty would make signal detection more difficult. The listener would always be uncertain as to which frequency region would contain the signal. If the listener was relying on simultaneous comparisons across critical bands, frequency uncertainty might have a different effect. If an across-frequency comparison strategy was a more effective way to locate a signal of random frequency, then frequency

uncertainty may be less likely to interfere with signal detection in this case.

Previous work on signal frequency uncertainty has shown the effect to be small (Buus, Schorer, Florentine, and Zwicker, 1986; Creelman, 1960; Green, 1961; Tanner, Swets, and Green, 1956; Veniar, 1958a; Veniar, 1958b). These findings have been difficult to interpret within the framework of the traditional view of signal detection and seem to provide support for the more recent view. In the study reported in Chapter 2, there were two primary goals. The first goal was to compare the same listeners' performance on signal detection tasks thought to rely on different types of auditory processing. The second goal was to include a task in which listeners are thought to rely on simultaneous, across-frequency comparisons.

Listeners' performance was compared across two tasks. The first task was referred to as the profile task. Listeners were asked to detect a change in the intensity of one component of a multicomponent waveform. Studies have shown that profile analysis relies on across-frequency comparisons (Green, 1983, 1988).

The second task was referred to as the noise task. Listeners were to detect a signal in wideband noise. Traditionally, the detection of a tone in noise has been thought to rely on successive comparisons of energy levels within a critical band (Fletcher, 1940; Weber, 1978). More recently, it has been thought that the process may be

based on some type of across-frequency comparison (Gilkey, 1987; Gilkey and Robinson, 1986; Green, 1988; Kidd, Mason, Brantley, and Owen, 1989).

Experimental evidence that supports the more recent across-frequency comparison view of auditory processing is growing. A second source of evidence for across-frequency auditory processing is studies that have shown that additional frequency information can be detrimental to signal detection (Neff and Green, 1987; Spiegel, Picardi, and Green, 1981;). In these studies, listeners were asked to detect the presence or absence of a signal presented simultaneously with additional frequency information (i.e., nonsignal tones). The results showed that signal detection thresholds were poorer when the frequencies of the nonsignal tones were selected randomly than when the nonsignal tone frequencies were fixed across a block of trials. These findings indicate that when the frequency composition of additional information was uncertain listeners were unable to ignore that information, and signal detection was impaired.

In Chapter 3, we summarize a study that extends previous work on the adverse effects of additional frequency information. The primary goal of the experiment was to determine if the detection of an attribute of a signal, amplitude modulation, was susceptible to these detrimental effects. In each experimental condition, a 1000-Hz, amplitude-modulated tone was presented in one

interval and a 1000-Hz, unmodulated tone was presented in the other interval of a 2AFC task. Listeners were asked to indicate in which interval the tone was amplitude modulated. Thus, the listener was not asked to detect the presence or absence of a signal as in previous studies, but rather a change in an ongoing signal.

On each trial interval, the modulated or unmodulated signal tone was presented simultaneously with nonsignal tones that we will refer to as masker tones. Listeners' performance was compared across two masker conditions, fixed and random. In the fixed masker condition, the frequencies of the masker tones were the same across a block of trials. In the random masker condition, the frequencies of the masker tones were selected randomly for each trial interval. The effect of masker uncertainty was determined by comparing the two masker conditions. It was expected that the detection of a change in an ongoing signal would be less susceptible to the deleterious effects of masker uncertainty than previous studies had shown.

A second issue of interest in this study was the across-frequency interaction between different types of auditory information. In this experiment, we will make the distinction between temporal and spectral information. Temporal information refers to the change in the amplitude of the stimulus over time. We will be referring to temporal information in terms of the waveform's envelope

fluctuation rate. Spectral information refers to the frequency composition of a waveform.

Two rates of amplitude modulation, 10 and 100 Hz, were used in the primary study. These rates of modulation were chosen because each is probably mediated by a different process for detection. Detection of 10 and 100 Hz modulation is best described in terms of a temporal and spectral process, respectively. Differences in listeners' thresholds for the two rates of modulation will be discussed in terms of temporal and spectral processes.

Another source of evidence for across-frequency auditory processing is a study conducted by Yost and Sheft (1989). They showed that across-frequency interference resulted when an amplitude-modulated masker tone was presented simultaneously with an amplitude-modulated signal tone. In Yost and Sheft's study, the signal and masker were modulated at 10 Hz and were separated in frequency by 2 octaves. Thus it is unlikely that the interference resulted from peripheral masking. Rather, the data suggest that the interference was between the envelope of the masker waveform and the envelope of the signal waveform (i.e., temporal interference).

In Chapter 4, we summarize a study in which we investigated several aspects of across-frequency interference. Our primary interest was in determining whether such interference occurred for another type of signal and masker waveform, two-tone complexes. We used

two-tone complexes because they produce a sinusoidal envelope similar to that produced by amplitude modulation. In each experimental condition, listeners were asked to detect the presence of envelope modulation in a 2AFC task. On both the signal and nonsignal trial intervals, a masker with a sinusoidal envelope was presented simultaneously.

We also explored the effect of increasing the envelope modulation rate of the signal and masker. At faster modulation rates, listeners are unable to follow the envelope fluctuations (temporal information) and have to rely on spectral information. We wanted to determine if across-frequency interference would occur when listeners had to rely on spectral information. We compared listeners' thresholds at three rates of modulation, 10, 40, and 160 Hz. We selected a rate of 160 Hz because detection is best described in terms of a spectral process. We selected a rate of 40 Hz because it is near the temporal/spectral breakpoint. The 10 Hz modulation rate provided a comparison with detection based on a temporal process.

Finally, we wanted to determine if across-frequency interference occurred when the signal and masker were modulated at different rates. We explored how the amount of interference changed with variation in the masker modulation rate. In this condition, the modulation rate of the signal was held constant at 10 Hz and the

modulation rate of the masker was varied. Masker modulation rates of 20, 40 and 80 Hz were used.

Two themes, across-frequency auditory processing and temporal vs spectral information, have been the major focus the work discussed thus far. Evidence from the studies presented indicates that a large portion of listeners' information was obtained from within-interval, simultaneous comparisons of different frequency regions.

In Chapter 5, we will describe a study that explored a related question. We wanted to determine listeners' abilities to discriminate an across-interval change in a signal. In contrast to the previous studies, only minimal information regarding the signal could be obtained from an within-interval, across-frequency comparison. The important comparison was between the two trial intervals.

As in Chapter 3, we used an attribute of a signal, amplitude modulation. A carrier that was amplitude modulated by a slower modulation rate (standard) and a carrier that was amplitude modulated by a faster modulation rate (comparison) were presented <u>sequentially</u> in 2AFC trials. Listeners were asked to discriminate which of the two amplitude-modulated carriers had the lower envelope frequency.

The first question we explored was what effect does carrier frequency have on rate discrimination. In this condition the carrier frequency was fixed across a block of trials. The task, then, was to compare across the two

trial intervals either temporal (slower modulation rates) or spectral (faster modulation rates) features of the stimulus. We compared listeners' thresholds at four carrier frequencies.

The second question we explored was what effect does varying the type of spectral cues available to the listeners have on rate discrimination. We compared listeners' thresholds for three spectral cue conditions. It was expected that thresholds would be similar at the slower modulation rates where discrimination is based on temporal cues, but would differ at the faster modulation rates where discrimination is based on spectral cues.

The third and final question we explored was what effect does the depth of modulation have on rate discrimination. Reduction in the depth of modulation reduces the amplitude of the carrier's sidebands. This reduction would presumably hinder spectral processing of amplitude modulation more than temporal processing. Thus it was expected that the greatest decrement in listeners' performance would be at the faster modulation rates where spectral cues are important.

We have briefly described the focus of the studies of this dissertation which is how listeners process complex auditory information. Each individual study will be presented in a separate chapter with an introduction that will summarize the specific issues related to that investigation. The experimental methods, results and

conclusions for each study will be also be presented within each chapter. Finally in Chapter 6, we will present a summary of the results of these investigations and the conclusions that can be drawn from this work.

CHAPTER 2

THE EFFECT OF SIGNAL FREQUENCY UNCERTAINTY IN PROFILE AND NOISE TASKS

Introduction

The detection of a change in spectral shape, designated as profile analysis, has been shown to depend on the intensity levels of components distributed over a wide spectral region and not simply on the intensity at one part of the frequency spectrum (Green, 1986; Green et al., 1984). In most previous studies of profile analysis, the observers knew where in frequency the spectrum was to be altered, that is, there was no uncertainty about the frequency locus of the signal. Because some results obtained in profile analysis suggest global processing of the auditory spectrum, it was unclear how uncertainty about the frequency locus of a potential spectral alteration would affect the detectability of such a change.

Spiegel et al. (1981) investigated signal uncertainty with tones and maskers that were randomly selected from 200 possible equal amplitude components. The frequencies of those components ranged between 300 and 3000 Hz, and were equally spaced on a logarithmic frequency scale.

In this experiment, we wanted to investigate signal frequency uncertainty when the masker energy was uniformly distributed on a log-frequency scale. Because of the log spacing and the fact that critical band width is proportional to center frequency, this uniform distribution results in approximately a constant number of tones per critical band.

Our interest was in comparing the effects of signal uncertainty with a profile masker and with a noise masker. Profile analysis appears to rely on across-frequency, within-interval comparisons (Green, 1983, 1988). Historically, in noise-masking experiments, it has been thought that the analysis process relied on within critical-band, across-interval energetic comparisons (Fletcher, 1940; Weber, 1978). However, more recently it has been suggested that the detection of a tone in noise may be based on some type of within-interval, across-frequency comparison (Gilkey, 1987; Gilkey and Robinson, 1986; Green, 1988; Kidd et al., 1987). We were interested in comparing the detection of changes in spectral shape using both multicomponent (profile) and noise maskers. The current experiment was aimed at one aspect of detection, comparing the effect of signal frequency uncertainty on the detectability of a tone in the profile and noise paradigms.

General Procedure

Ten, normal-hearing listeners participated in this experiment. All listeners were college students recruited through advertisements placed in the student newspaper. They were paid at an hourly rate for their participation. The listeners that participated in this experiment had previous experience in tone-detection tasks, and received 1 to 2 hours of practice prior to data collection.

The observers were seated in individual, sound-treated rooms. The stimuli were presented diotically over Sennheiser HD 414 SL earphones, and both phones were driven in-phase. All the stimuli were generated digitally, played over digital-to-analog converters (D/A's) at a sampling rate of 25,000 Hz, and low-pass filtered at 10,000 Hz. The duration of the stimulus was 100 msec, including 5-msec $\cos^2$ rise/decay ramps.

On each stimulus presentation, the overall level of the stimulus was chosen, at random, from a 20-dB range in 1-dB steps. This random level procedure was used to reduce the possibility of listeners using either the overall stimulus level or the absolute level in one critical band as a cue for detection of the signal.

Two-alternative, forced-choice trials (AFC) were used. In one interval, the standard alone was presented. In the other interval, a signal was added to the standard. The signal occurred with equal a priori probability in the first or second interval.

Method

Two conditions were completed for both the profile and noise tasks in this experiment. In the first, referred to as the "uncertain" condition, listeners were presented with the multicomponent waveform or noise (standard) in one interval. In the other interval, one of 21 possible signal frequencies was selected randomly on each trial and added to the standard. On each trial of this condition, the subject was to report which interval contained the signal.

The second condition will be referred to as the "certain" condition. The procedure for this condition was identical to that for the uncertain condition, except for one important difference. Prior to each trial, a tone of the same frequency as the signal to be detected was presented for a duration of 100 msec. The first interval of a trial began 400 msec after the termination of this tone. The tone was presented at a level of 60 dB which was clearly audible to the listener. Thus, the subject heard the frequency of the signal prior to each trial. The difference in signal threshold measured in these two conditions was used as a measure of the effect of signal frequency uncertainty.

Each listener first completed the certain condition and then completed the uncertain condition, for both the profile and noise tasks. These two conditions were run at the end of a series of conditions, each utilizing the same

certain and uncertain paradigms. Given the extensive experience of the listeners, it is unlikely that there was any effect of presentation order on these data. In addition, no practice effect was evident in the data.

The amplitude of the signal was varied adaptively to estimate the level that produced 79% correct detection (Levitt, 1971). The amplitude was decreased by 4 dB following three correct responses and increased by 4 dB following one incorrect response. After 4 "reversals," the step size was reduced to 2 dB. Fifty trials were run per block and each block produced approximately 14 reversals. Thresholds were determined by averaging the signal level across the last even number of reversals, excluding the first four reversals. For each condition, the reported threshold is the average of twenty-four such estimates for each subject.

Profile Task

In this task, the listeners detected a change in the intensity of one component of a multicomponent waveform. The "standard" waveform consisted of 21 equal-amplitude sinusoid components. The components ranged in frequency from 200 to 5000 Hz and were spaced logarithmically with a ratio of 1.175. The phase of each component was chosen randomly. One "standard" waveform was used for all presentations in both the certain and uncertain conditions. The median presentation level was 60 dB SPL.

The "signal" waveform was a single sinusoid added in-phase to one component of the standard. Thus there were 21 potential signals that had the same frequencies as the components of the standard. The possible signals ranged in frequency from 200 to 5000 Hz and were equally spaced on a logarithmic frequency scale.

Previous work has shown that the detectability of an increment to a single component in a multicomponent waveform varies as a function of frequency (Green, Onsan and Forrest, 1987). For that reason, equal-amplitude tones were not employed. The sound pressure level (SPL) values for the signals were generated as a function of frequency in accordance with Bernstein and Green's (1988) equation for equal detectability,

$$EDL_p = 20\ [\log(f/1148)]^2 - 0.07, \qquad (1)$$

where EDL_p is the equal-detectability level for profiles in dB, f is the frequency of the signal in Hz, and 0.07 dB adjusts the equation to equal 0-dB correction at 1000 Hz. EDL_p, then, is the detectability relative to detectability at 1000 Hz. Thus at 1000 Hz the EDL_p is 0 dB, at 4000 Hz it is 5.8 dB, and at 250 Hz it is 8.7 dB. We will report as "signal threshold" the signal-to-standard level, in dB, minus the EDL_p value for each frequency. This makes the threshold value essentially independent of signal frequency.

Results and discussion

Listed in Table 2-1 are the subjects' thresholds for the certain and uncertain signal frequency conditions in the profile task. In Table 2-1 and elsewhere S. E. refers to the standard error of the mean, computed across all listeners and replications.

Table 2-1

Listeners' Thresholds for the Detection of an Increment in a Single Component of the Profile, dB Relative to EDL_P

Subject	Certain	Uncertain	Difference
1	-21.8	-17.7	4.1
2	-20.5	-16.4	4.1
3	-20.1	-14.3	5.8
4	-19.9	-14.9	5.0
5	-19.1	-16.3	2.8
6	-19.0	-16.6	2.4
7	-17.0	-16.9	0.1
8	-16.8	-16.4	0.4
9	-14.3	-13.2	1.1
10	-11.5	- 9.3	2.2
AVERAGE	-18.0	-15.2	2.8
S. E.	0.27	0.22	0.61

All listeners performed better in the certain condition than in the uncertain condition. As a measure of the effect of signal frequency uncertainty, we calculated the difference in listeners' thresholds for the certain and uncertain conditions. The differences between the two conditions ranged from 0.1 to 5.8 dB, depending on the listener. The average difference between the two conditions was 2.8 dB. For listeners 7 and 8, however, the difference was less than 1 dB. The average standard deviation of the threshold estimates, for all subjects and for both conditions combined, was about 2.7 dB (range = 2.01 to 4.00 dB). The relatively small uncertainty effect is consistent with a previous study of frequency uncertainty using a multicomponent complex (Spiegel et al., 1981).

The data indicate that those listeners with lower thresholds (better sensitivity) in the certain condition showed larger effects of signal uncertainty. That is, the better listeners showed more effect of signal frequency uncertainty. Figure 2-1 presents the effect of uncertainty as a function of the signal threshold in the certain condition. The correlation obtained for the ten observers indicated a moderate negative correlation ($r = -0.62$). We will postpone a discussion of these results until after presenting the noise task.

Randomizing the overall stimulus level reduces the possibility of listeners using the absolute intensity

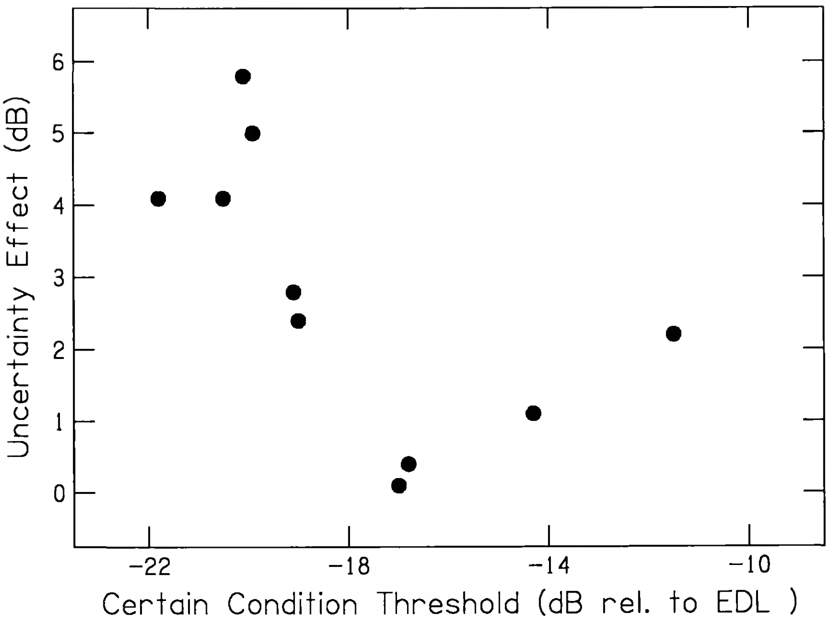


Figure 2-1. The magnitude of the uncertainty effect in the profile task is plotted as a function of listeners' thresholds when a tone having the same frequency as the signal is heard prior to each trial (certain condition). The correlation obtained was -0.62.

level in one critical band as a cue for the detection of the signal. The effect of level randomization is that a larger signal-to-standard ratio is needed for signal detection to be based solely on intensity. This ratio varies as a function of the range of level variation and the adaptive rule being used (see Green, 1988, Appendix A). If absolute intensity level were the only cue available to listeners in the profile task, then the expected signal threshold would have been 2.0 dB (Green, 1988, p. 20).

As can be seen from the data that were presented in Table 2-1, listeners' thresholds are much better than the prediction based solely on an intensity cue. From these data, it is concluded that listeners did not rely on a comparison of a single critical band across trial intervals. Rather, it is likely that detection was based on a simultaneous comparison of two or more critical bands within a single trial interval.

Noise Task

In this task, we investigated listeners' abilities to detect a signal of random frequency in a wideband noise. The noise was generated digitally and was Gaussian distributed. The noise was low-pass filtered at 10,000 Hz and had a median spectrum level of 30 dB SPL. Different noise samples were obtained for each trial by choosing randomly the starting point in a 32-K buffer that was

filled with noise samples. The same 21 potential signals that were used in the profile task were also used in this task. To make the tones nearly equally detectable in noise, we adjusted the amplitudes of the tones as a function of frequency (Green, McKey and Licklider, 1964) so that the energy in decibels was,

$$EDL_N = 2(f/1000) - 2, \qquad (2)$$

where EDL_N is the correction in decibels and f is the frequency of the tone in Hz. The constant, 2 dB, was chosen so that the correction at 1000 Hz is 0 dB. The threshold reported will be the signal energy to noise power density in dB, $10 \cdot \log(E/N_o)$, minus EDL_N.

Results and discussion

Listed in Table 2-2 are subjects' thresholds for the certain and uncertain signal frequency conditions in the noise task. Performance in the uncertain condition was on average 2.6 dB poorer than performance in the certain condition.

Green et al. (1964) established that the expected threshold for the detection of a 1000 Hz tone in noise is 10 dB. The average threshold in the certain condition of 10.5 dB, which was presented in Table 2-2, is consistent with this expectation. With the exception of subject 10, all of the individual thresholds in the certain condition were within +/- 2 dB of this value.

Table 2-2

Listeners' Thresholds for the Detection of a Sinusoid Signal in Noise, dB Relative to EDL_N

Subject	Certain	Uncertain	Difference
1	10.1	12.2	2.1
2	11.4	13.6	2.2
3	9.3	13.2	3.9
4	8.9	12.4	3.5
5	8.9	13.1	4.2
6	10.3	12.3	2.0
7	10.6	13.7	3.1
8	10.4	12.9	2.5
9	11.8	14.0	2.2
10	13.5	14.2	0.7
AVERAGE	10.5	13.2	2.6
S. E.	0.15	0.10	0.33

Previous studies have shown (Buus et al., 1986; Creelman, 1960; Green, 1961; Tanner et al., 1956; Veniar, 1958a; Veniar, 1958b), the effect of signal frequency uncertainty is small. The average difference between the two conditions, 2.6 dB, is about the same as that found in the profile task. The range of threshold differences (uncertain - certain) is not the same as that found in the profile task. The differences between the two conditions

ranged from 0.7 to 4.2 dB. This range of 3.5 dB is smaller than that found in the profile task (range = 5.7). The average standard deviation of the threshold estimates for all subjects and for both conditions combined was 1.6 dB (range = 1.0 to 2.63 dB).

As in the profile task, we compared listeners' thresholds in the certain condition with their difference between the two conditions. Figure 2-2 presents the effect of uncertainty as a function of the certain condition threshold. The correlation obtained for these data indicated a strong negative correlation ($r = -0.88$). Those subjects who performed better in the certain condition showed larger effects of uncertainty.

General Discussion of Profile and Noise Tasks

Comparing the results from the previous two tasks, two trends are apparent. First, regardless of the task (profile or noise), uncertainty about the signal's frequency hinders its detection. Listeners were better able to detect the signal if they heard a tone of the same frequency prior to the trials. In both the profile and noise tasks the effect of uncertainty was small, between two and three dB for both tasks. Even though the effect of uncertainty was small in terms of dB, it should be noted that the difference in the means (i.e., the change in threshold due to uncertainty) for both tasks was greater than 5 times the standard error of the mean and

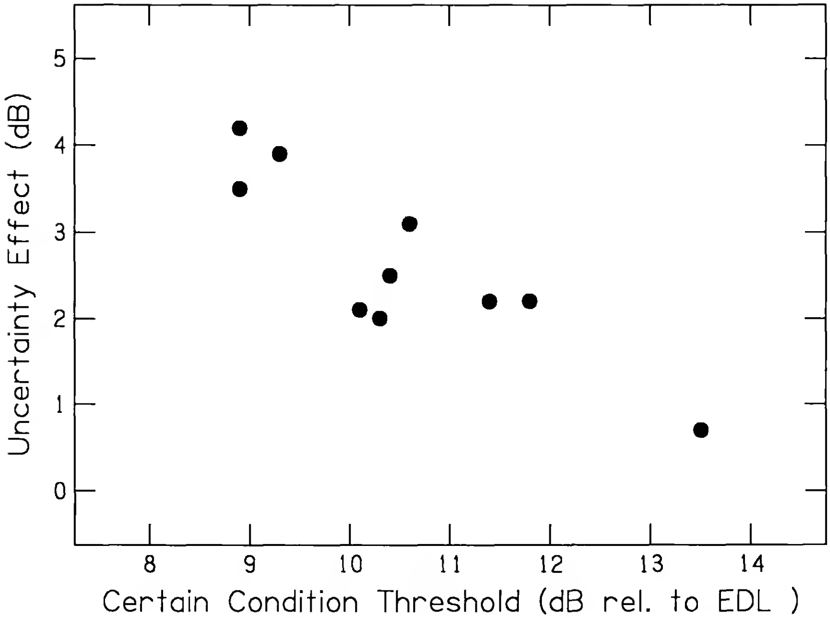


Figure 2-2. Same as Figure 2-1, except that the masker was wideband noise. The correlation obtained was -0.88.

statistically significant ($p < 0.05$). Although the effect of signal frequency uncertainty was approximately the same for the profile and noise tasks in terms of dB, it is difficult to generalize about the uncertainty effects because the psychometric functions for the two tasks are different (Raney, Richards, Onsan, and Green, 1989).

A second trend was also noted. In both profile and noise tasks, a comparison between listeners' thresholds in the certain condition and their difference between the two conditions (certain minus uncertain) yielded at least moderate correlations (profile, $r = -0.62$; noise, $r = -0.88$). Those listeners who performed better in the certain conditions showed larger effects of uncertainty.

There is, however, a potential problem in interpreting the significance of these correlations. This problem is due to the dependence of the uncertainty effect values (certain threshold minus uncertain threshold) on the certain thresholds. Because of this relation, a negative correlation may occur in the absence of a real effect. If the thresholds in the certain and uncertain conditions were completely independent, we could expect an r value of -0.69 (s.d. = 0.2) due to chance.

The two conditions in this experiment, however, were not completely independent. The correlation between the certain and uncertain thresholds was 0.79 for the profile task and 0.71 for the noise task. Simulations were conducted to determine the likelihood that the obtained

correlations between the certain conditions and the uncertainty effects would have been due to chance. For the profile task, the obtained correlation of -0.62 would have been expected at a level of about 0.15 (s.d. = 0.02). For the noise task, the obtained correlation of -0.88 would have been expected at a level of about 0.003 (s.d. = 0.002). Thus the profile correlation is approaching significance and the noise task is significant at the 0.003 level.

Because the same listeners completed both the profile and noise tasks, we can compare their performance across tasks. The correlation between thresholds obtained for the certain or uncertain conditions were at least moderate ($r = 0.77$--certain conditions; $r = 0.64$--uncertain conditions). Those listeners that performed better in the profile task also performed better in the noise task.

There is clearly some similarity in listeners' performance across the two tasks. However, there is less agreement among observers as to the effects of uncertainty. The correlation of uncertainty scores between the two types of maskers is only 0.31.

Summary

In this study, we were interested in comparing the effects of signal frequency uncertainty on the detection of a tone presented with a profile masker and with a noise masker. The results indicated that uncertainty about a

signal's frequency elevates detection thresholds, regardless of the masker type. This effect of uncertainty was approximately 3 dB, in both the profile and noise tasks. Comparing the results across tasks, we found that those listeners that performed better in the profile task also performed better in the noise task.

CHAPTER 3

MASKER UNCERTAINTY AND THE DETECTION OF AMPLITUDE MODULATION

Introduction

Spiegel et al. (1981) and Neff and Green (1987) established the detrimental effect of masker uncertainty on the detection of sinusoidal signals. In this study, we explored whether the same set of principles applied to the detection of an attribute of a signal, namely amplitude modulation. In this case, the detection of the signal was not at issue. Rather, we wanted to determine if the listener could detect changes in an ongoing signal, specifically, dynamic changes in the amplitude of the signal.

We argue that masking can be described as the sum of two processes. The first process we call peripheral masking. Historically, this term has been used to refer to conditions in which the threshold for a signal is increased (i.e., signal is more difficult to detect) due to the presence of nonsignal energy in the signal frequency channel. Nonsignal energy could be, for example, noise or tones that produce energy near the signal frequency. The basis of peripheral masking is a lowered signal-to-noise ratio in the signal channel.

The second process we refer to as central masking. We will be using this term as it was used by Watson and Kelly (1981). They used the term central masking to describe limits on the discrimination of complex auditory sounds that can be manipulated by stimulus uncertainty or by overtraining. The focus of our discussion in this chapter will be on the effects of stimulus uncertainty. We should note that we do not use central masking as Zwislocki (1970) did to refer to the increase in the threshold of audibility in one ear due to the presence of a sound in the other ear.

Stimulus uncertainty has been varied most often by manipulating the probability of the stimulus, either signal or masker or both. In this experiment, we will manipulate the probability of the masker. A common approach used to change the masker probability has been to vary the total number of potential tones from which the specific tones composing a masker can be selected. As the number of possible masker tones is increased, the predictability of the next occurring masker decreases. Increases in the total number of masker tones, however, may also increase the amount of peripheral masking. The basic problem is how to separate central and peripheral masking, since in most experiments increases in one are accompanied by increases in the other.

In this investigation, we wanted to determine the effects of masker uncertainty on the detection of

amplitude modulation. In the experiments that follow, we present an experimental approach that attempts to estimate the relative contributions of peripheral and central masking. Before beginning a description of these experiments, we briefly review the work of Spiegel, Picardi, and Green (1981), Spiegel and Green (1982) and Neff and Green (1987). They studied how masker uncertainty affects the detectability of a signal.

Previous Experiments

Spiegel et al. (1981) investigated listeners' abilities to detect an increment in one component of a multicomponent stimulus. They compared listeners' thresholds in conditions of signal frequency uncertainty to conditions of masker uncertainty. In the uncertain signal conditions, the frequency of the component to be incremented was selected randomly for each trial. In the uncertain masker conditions, the frequencies of the nonsignal components of the masker were chosen randomly on each trial. Results indicated that listeners' discrimination thresholds were poorer in the conditions of masker uncertainty than in the conditions of signal uncertainty. This result was independent of the number of components composing the masker waveform.

Spiegel and Green (1982) compared the effects of signal frequency and masker uncertainty using a detection task. In their study, listeners were asked to detect a

sinusoidal signal in noise. As in the previous study, signal uncertainty was manipulated by selecting randomly the signal frequency on each trial. In the uncertain masker conditions, a different noise waveform was selected for each trial. For both uncertainty conditions, listeners' abilities to detect the signal were poorer by 2-5 dB.

Neff and Green (1987) provided additional evidence that masker uncertainty may result in a sizeable decrement in performance. They asked listeners to detect a sinusoidal signal of fixed frequency presented simultaneously with a multicomponent masker. In each condition, the frequencies of the masker components were selected randomly . Thus in each condition, listeners were uncertain as to the spectral composition of the maskers. The number of masker components was held constant across a block of trials and ranged from 2 to 100. Neff and Green used a different masker for each interval of a trial. Spiegel and his associates had used the same masker for both intervals of a given trial.

Neff and Green compared thresholds from the conditions of masker (spectral) uncertainty with the same listeners' thresholds measured for known signals (250, 1000, and 4000 Hz) in wideband noise. A surprising finding was that 3 or 4 component maskers produced as much masking as wideband noise, and that 10 component maskers produced 10 to 20 dB more masking than the noise. Neff

and Green concluded that the listeners were unable to ignore the information that was spectrally uncertain, although it would have been advantageous for them to do so. Even in conditions where there was little or no masker energy near the signal frequency (i.e., few components composing the masker), performance appeared to be hindered.

A second experimental manipulation indicated that when masker uncertainty was reduced, listeners' abilities to detect the signal improved. Conditions were run in which the same masker was used for both intervals of a given trial. In all cases, fixing the masker across intervals resulted in an improvement in performance.

Although the magnitude of these results would be difficult to explain based on a traditional view of masking (i.e., peripheral masking), Neff and Callaghan (1987) investigated this possibility. One could argue that the masking found in the previous study was due to peripheral masking (i.e., the frequency of the masker component(s) was near the signal frequency), rather than central masking (i.e., uncertainty about the frequency of the masker component(s)).

To minimize peripheral masking, Neff and Callaghan excluded masker components from a 160-Hz region around the 1000-Hz signal. For maskers with 2 and 4 components, this procedure resulted in no decrease in the amount of masking. For maskers with 6, 8, or 10 components there

was a small, but significant decrease in masking (5 dB). This reduction in masking suggests that peripheral masking contributed in part to the findings of the previous experiment. However, for all the maskers with 10 or fewer components, 37-40 dB of masking still resulted. These large amounts of masking are difficult to explain in terms of peripheral masking. It seems likely that central masking also played a role in the elevated detection thresholds.

These experiments have provided evidence that detection of a known signal may be hindered when the frequency composition of a masker is randomly selected on each trial or each presentation. One common feature across the previous conditions of masker uncertainty was that the signal was unchanged within a trial interval. Signal frequency was always constant and listeners were asked to detect either the presence of a signal or a change in its intensity from one interval to the next. It is clear from these studies that central masking makes the detection of a signal more difficult.

In this study, we investigated whether the ability to discriminate an attribute of a signal is also susceptible to the deleterious effects of central masking. The purpose of this work was to extend the previous research by examining whether masker uncertainty would influence the detection of amplitude modulation. Listeners were asked to discriminate whether a signal was steady in

amplitude or sinusoidally modulated. The signal was always clearly audible; at issue was whether the amplitude of the signal was constant or varying over time. We will describe two methods used to estimate the relative contributions of peripheral and central masking on the detection of amplitude modulation.

General Procedure

A total of five, normal-hearing listeners participated in the study. All the listeners were college students recruited through advertisements placed in the student newspaper. They were paid at an hourly rate for their participation. Each of the listeners received several hours of practice prior to data collection.

The observers were seated in individual, sound-treated rooms. The stimuli were presented diotically over Sennheiser HD 414 SL earphones, and both phones were driven in-phase. All the stimuli were generated digitally, played over D/A's at a sampling rate of 25,000 Hz, and low-pass filtered at 10,000 Hz. The duration of the stimulus was 100 msec in the preliminary work and 400 msec in the main experiment. Five-msec $\cos^2$ rise/decay ramps were used for all stimulus presentations.

The same task was used throughout the study. Listeners were asked to detect an amplitude-modulated signal in 2AFC trials. The signal waveform may be described as follows:

$$s(t) = [1 + m \cos(2\pi f_m t)] * [\cos(2\pi f_c t)], \qquad (3.1)$$

where m is the depth of modulation, f_m is the rate of modulation in Hertz, and f_c is the frequency of the carrier.

In the signal interval, listeners were presented with a 1000-Hz carrier that was amplitude modulated. In the nonsignal interval, an unmodulated, 1000-Hz tone was presented. Three rates of amplitude modulation were employed. In the preliminary work, the signal was modulated at a rate of 40 Hz. In the main experiment, modulation rates of 10 and 100 Hz were used.

Listeners' thresholds were determined varying adaptively the depth of modulation (reported as dB, 20 log m) of the signal. A 2-down, 1-up procedure (Levitt, 1971) was used to estimate a threshold that corresponded to 70.7% correct detection. The depth of modulation was decreased by 4 dB following two correct responses and increased by 4 dB following one incorrect response. After 4 "reversals," the step size was reduced to 2 dB. Fifty trials were run per block and each block produced approximately 14 reversals. Thresholds were determined by averaging the signal modulation depth in dB across the last even number of reversals, excluding the first four reversals.

On each stimulus presentation, the overall level of the stimulus was chosen at random from a 20-dB range in

1-dB steps. This random level procedure was used to reduce the possibility of listeners using either the overall stimulus level or the absolute level in one critical band as a cue for detection of the signal.

The number of components composing the masker was varied, and the frequencies of the masker components were either fixed or selected randomly on each presentation. In the preliminary study, the number of sinusoids ranged from 0 (no masker) to 20. In the main experiment, maskers were composed of 0, 1, and 10 tones. A given masker was generated by selecting randomly and without replacement the appropriate number of sinusoids from a pool. Twenty equal-amplitude tones, ranging in frequency from 200 to 5000 Hz, made up the pool. The frequencies of the 20 possible masker tones were determined using logarithmic spacing with a ratio of 1.175. This spacing resulted in approximately one tone per critical band. The 1000-Hz masker component was omitted since that was always the frequency of the signal.

Method

In the preliminary work, the number of tones composing a masker varied from 0 to 20, and was held constant across a block of trials. For each tone number condition, the tones composing the masker were selected randomly for each trial interval.

By varying the number of tones used as a masker we could vary masker uncertainty and, hence, the amount of central masking. In fact, as the number of masker tones varies from 0 to 20, the amount of masker uncertainty will first increase and then decrease. This can be confirmed by noting that the selection of 2 tones out of 20 produces the same uncertainty as the selection of 18 tones out of 20. Maximal uncertainty would occur when 10 tones are selected out of the 20 possible tones. Thus, we expect the amount of central masking to follow an inverted U shape function, being maximum when 10 tones are selected from the pool of 20 tones.

Peripheral masking, on the other hand, would only increase with increases in the number of masking tones. For example, there would be no peripheral masking when no maskers were present and it would reach a maximum when all 20 masker tones present. The total masking observed for the other numbers of masker tones will be some combination of peripheral and central masking, as the data will clearly show.

The problem with this preliminary study was that we had no firm way of assessing the relative amounts of peripheral and central masking. This problem led us to the main experiment, where we used a subtractive method. Suppose that we fixed the frequencies of the masking tones across a block of trials. If the frequencies of tones were <u>fixed</u> on each trial, then there would be no

uncertainty and hence no central masking. The threshold for amplitude modulation would then reflect only peripheral masking. If the same number of masker tones were used, but their frequencies selected at random on each trial, the same average amount of peripheral masking would be present, but in addition, some central masking would be created. In the main experiment, we determined listeners' thresholds for both the fixed and random conditions. We then used the difference in thresholds between the random and fixed conditions as our estimate of the amount of central masking.

In the main experiment, we used 1 or 10 masking tones. Ten masking tones will produce the highest value of masker uncertainty and one masking tone will produce a value near the minimum. We also compared two rates of amplitude modulation. We used a slow rate, 10 Hz, where the discriminable cue is probably based on some temporal process and a much faster rate, 100 Hz, where a spectral cue is the probable basis of the discrimination. In the preliminary work, we used a modulation rate of 40 Hz. In retrospect this was a poor choice because at that rate of modulation it is not clear whether the important detection cue is temporal or spectral.

It should be noted that the frequency ranges from which the masker tones could be selected differed across the modulation rates. When the signal was modulated at 10 Hz or 40 Hz the masker tones were selected from 200-851 Hz

and 1175-5000 Hz. When the signal was modulated at 100 Hz the masker tones were selected from 200-725 Hz and 1380-5000 Hz. These ranges were selected so that the frequency spacing between the sidebands of the modulated signal and the closest possible masker tones was similar regardless of the modulation rate.

Results and Discussion

Results for the preliminary study are shown in Figure 3-1. The number of masking tones used for the threshold estimates was varied from 0 to 20. The results show the expected inverse U function that we described earlier. In the no masker condition (NM) there was neither peripheral nor central masking and the average threshold for discriminating amplitude modulation is -23.4 dB. With a 20-tone masker present there was no central masking, therefore all the masking must have been peripheral. The threshold in this condition is -10.6 dB thus the amount of peripheral masking must be -12.8 dB. This result is consistent with Neff and Green's (1987) comparison between 20-tone fixed and random maskers that also found 13 dB of peripheral masking.

A comparison between the 20-tone condition and the 5, 10, 15, and 18 tone conditions suggests that a lower bound on the estimate of central masking would be 4 dB. This estimate is calculated by subtracting 13 dB from the total amount of masking in each of the conditions, and averaging

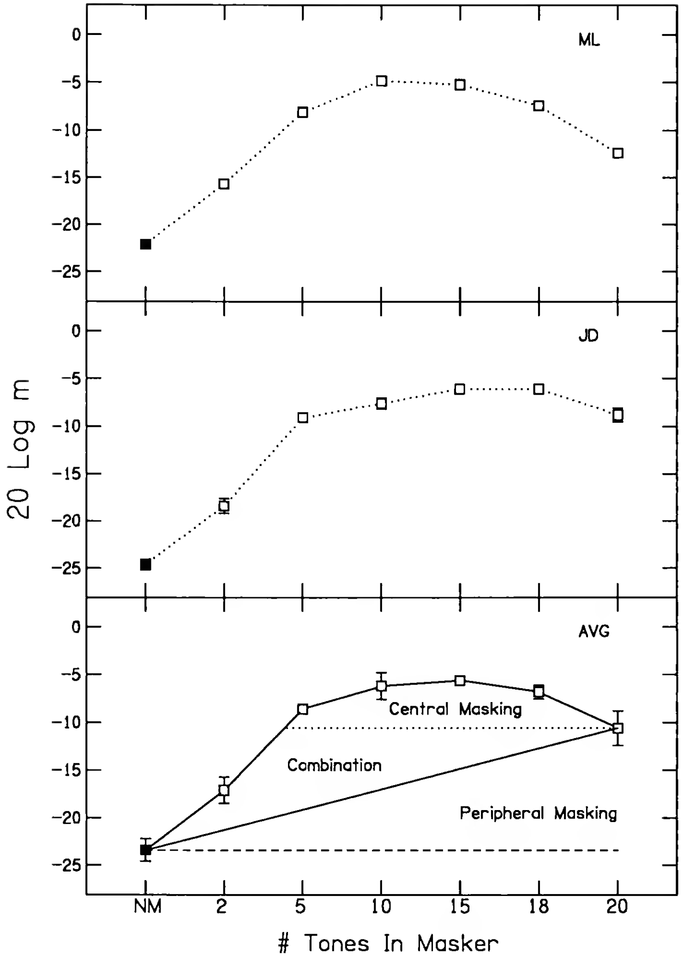


Figure 3-1. Two listeners' thresholds (20 log m) are plotted as a function of the number of tones composing the masker and for the no masker (NM) condition. The average thresholds across listeners are also plotted.

across conditions. The estimate is a lower bound because less than 13 dB of peripheral masking would be expected in those conditions with fewer masker tones. The relative masking contributions in the 2-tone condition cannot be obtained by this method.

The analysis of these preliminary data provides a general conclusion that both peripheral and central masking contributed to a decrease in listeners' abilities to detect a 40-Hz amplitude-modulated tone. The problem is that we can only estimate roughly the relative contributions of peripheral and central masking for each masker condition. To remedy this problem, we used a second procedure - a subtraction method.

This procedure allowed us to quantify more accurately the relative contributions of peripheral and central masking. We determined the amount of masking produced by a fixed set of masker tones. This gave us a measure of peripheral masking. We determined the amount of masking produced by choosing randomly a different set of masker tones on each trial interval (i.e., peripheral plus central masking). Finally, we took the difference of the two masking amounts to get a measure of central masking. We also examined how the amounts of peripheral and central masking changed as a function of the modulation rate of the signal.

Listeners' thresholds for the 10-Hz modulated signal in the 1 and 10 tone masker conditions are shown in

Figures 3-2 and 3-3, respectively. Listeners' thresholds for the 100-Hz modulated signal in the 1- and 10-tone masker conditions are shown in Figures 3-4 and 3-5, respectively.

The dependent variable on all four graphs is the threshold for amplitude modulation, 20 log m. Data for one listener for the no masker (NM) and the random (RND) conditions is shown in each panel. For the fixed conditions, the amount of masking produced by single frequencies (in the 1-tone masker conditions) and for sets of masker tones (in the 10-tone masker conditions) is presented. The average amount of masking in the fixed conditions is shown by the horizontal dashed line. To simplify the discussion of the data, we next present summary tables of the results.

In Tables 3-1 and 3-2, we summarize the results for each masker condition when the signal was modulated at 10 and 100 Hz, respectively. In each table, we present the estimates of the amounts of central and peripheral masking for each listener and the averages across listeners.

When the signal was modulated at 10 Hz (see Table 3-1), the average amounts of peripheral masking in the 1- and 10-tone masker conditions were small, 2.2 and 4.1 dB, respectively. The average amounts of central masking were also small, 1.1 dB in the 1-tone condition and 4.3 dB in the 10-tone condition. Because all of the masking amounts are small, we conclude from these data that the 10-Hz

Figure 3-2. Four listeners' thresholds (20 log m) are plotted as a function of the single tone masker frequency for the fixed condition. The signal was amplitude modulated at a rate of 10 Hz. Thresholds are also plotted for the no masker (NM) condition and for the listeners' obtained thresholds in the single tone random masker condition (RND). The dotted horizontal line represents listeners' expected thresholds for the single tone random masker condition.

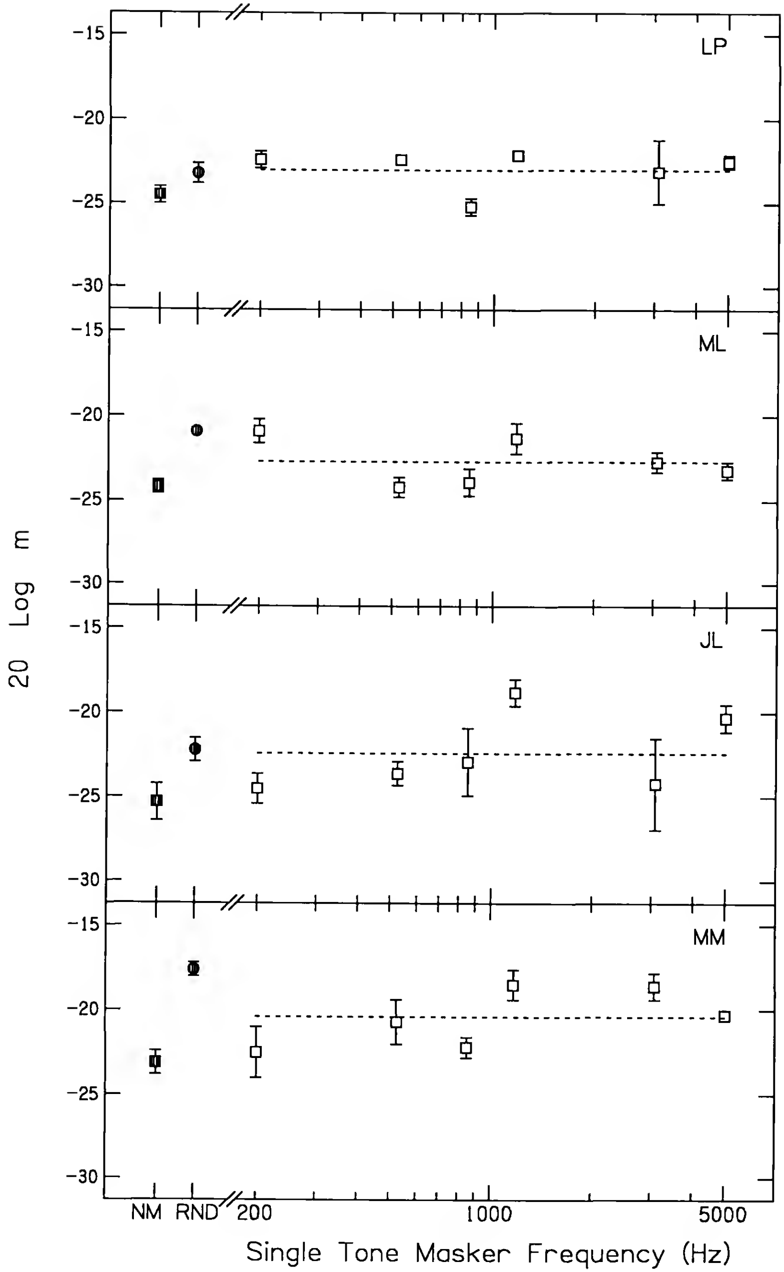

LP
ML
JL
MM
-15
-20
-25
-30
20 Log m
NM
RND
200
1000
5000
Single Tone Masker Frequency (Hz)

Figure 3-3. Four listeners' thresholds (20 log m) are presented for the 3, 10-tone maskers selected for the fixed condition. The signal was amplitude modulated at 10 Hz. Listeners' thresholds are also presented for the no masker (NM) condition and for the 10-tone random masker condition (RND). The dotted horizontal line represents listeners' expected thresholds for the random masker condition.

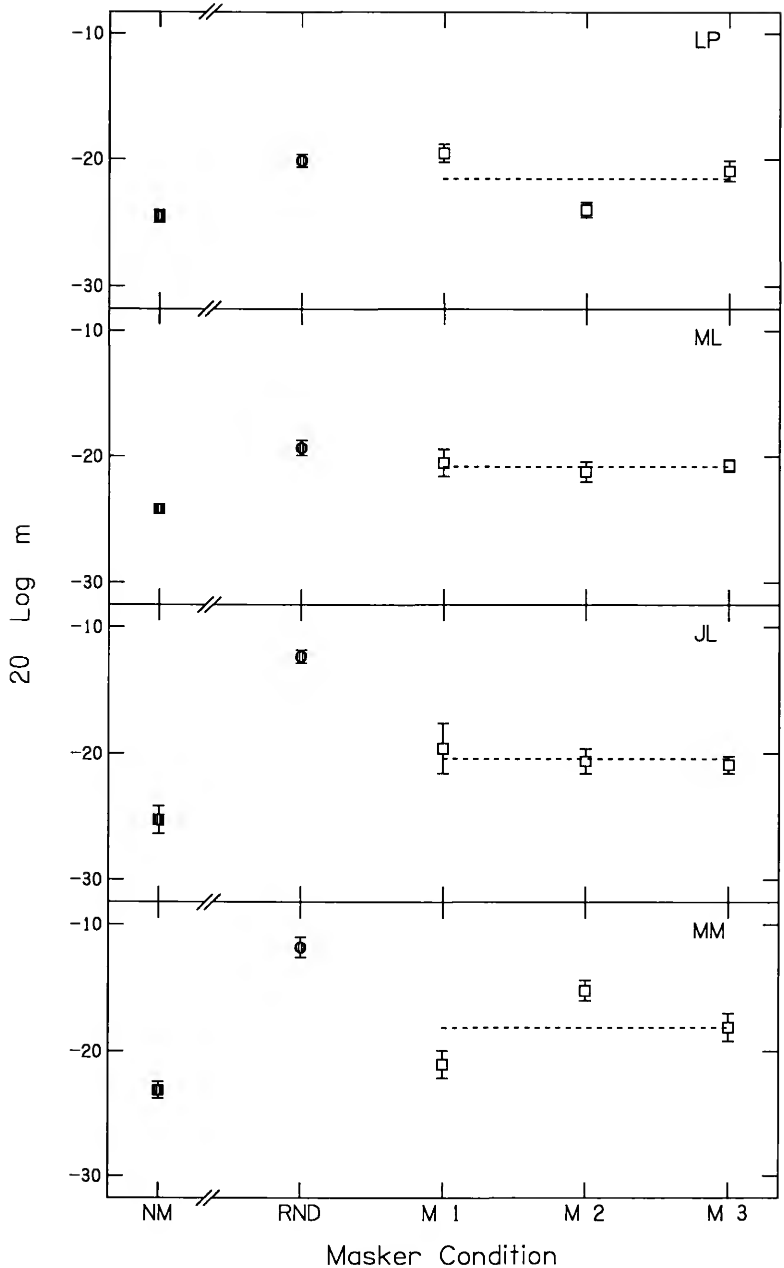

LP
ML
JL
MM
-10
-20
-30
20 Log m
NM
RND
M 1
M 2
M 3
Masker Condition

Figure 3-4. Same as Figure 3-2, except the signal was amplitude modulated at 100 Hz.

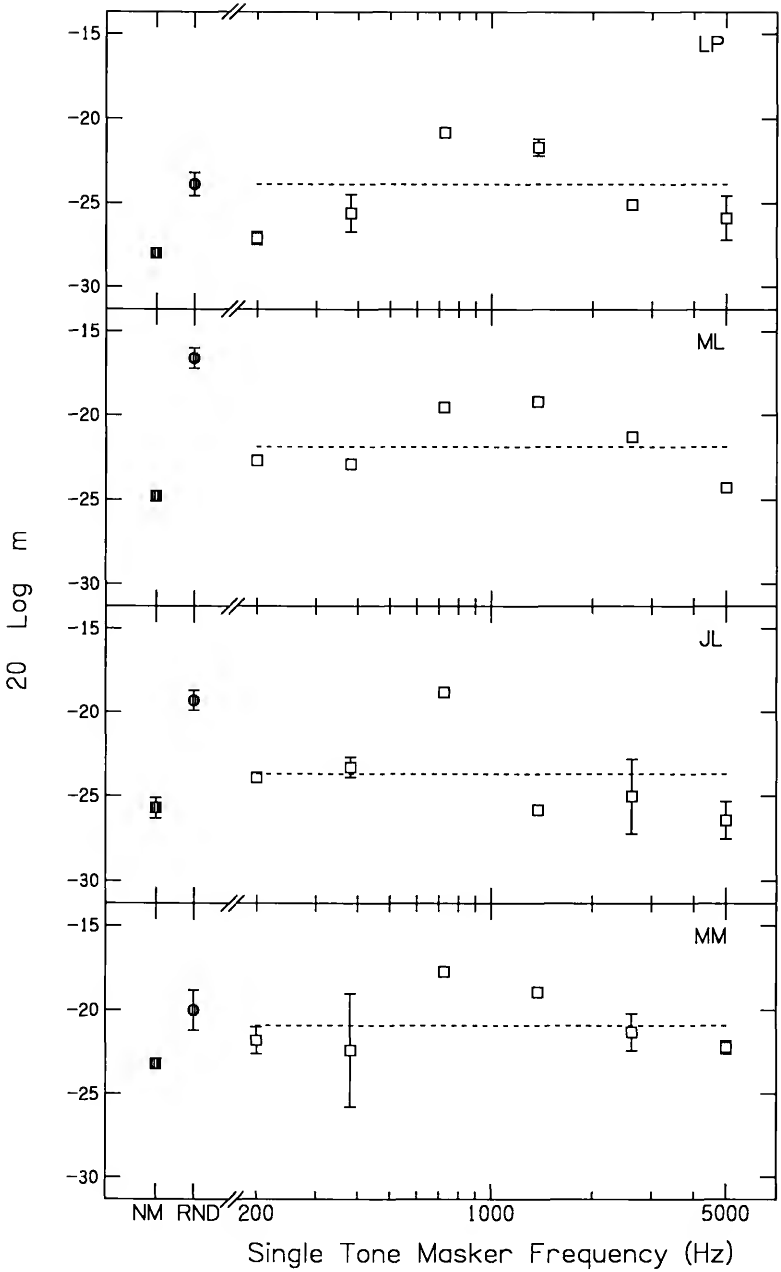
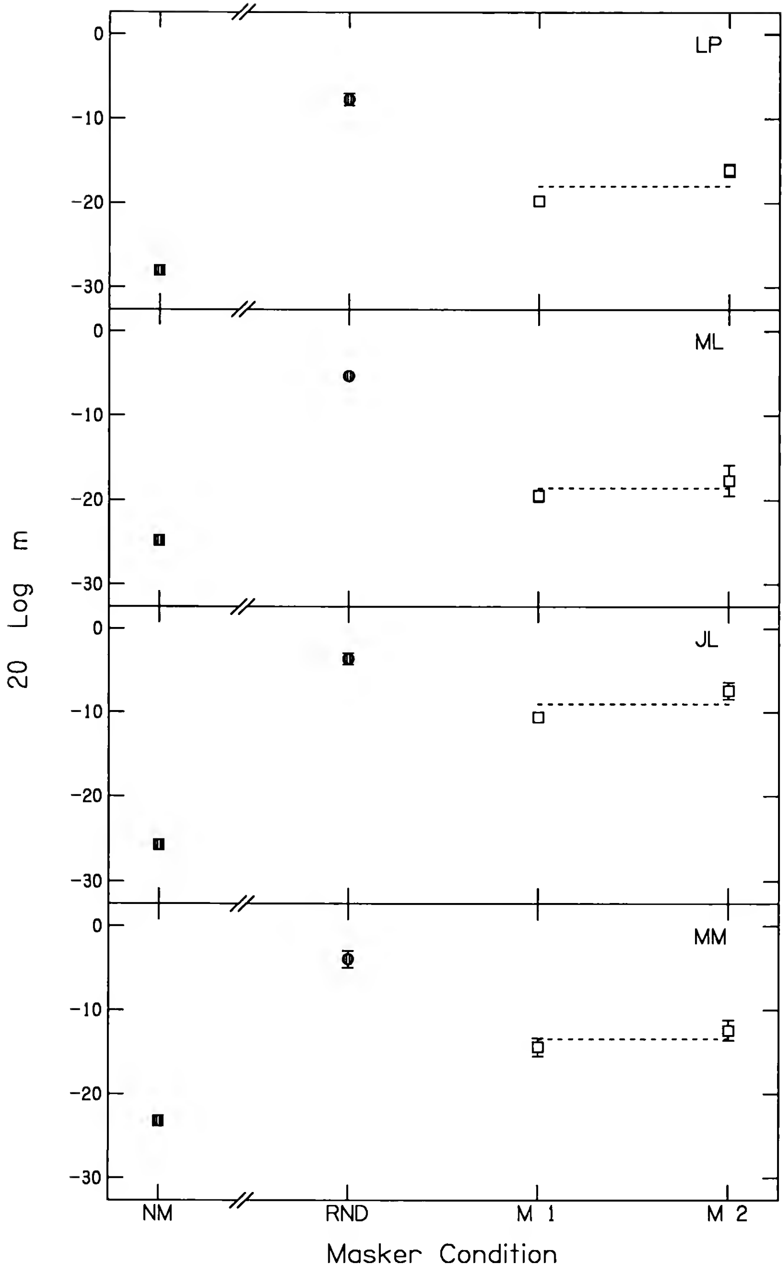

LP
ML
JL
MM
-15
-20
-25
-30
20 Log m
NM
RND
200
1000
5000
Single Tone Masker Frequency (Hz)

Figure 3-5. Same as Figure 3-4, except the signal was amplitude modulated at 100 Hz and thresholds (20 log m) are presented for 2 rather than 3, 10-tone maskers.



LP
ML
JL
MM
0
-10
-20
-30
20 Log m
NM
RND
M 1
M 2
Masker Condition

Table 3-1

Amounts of Peripheral and Central Masking for Each Masker Condition When the Signal Was Modulated at 10 Hz

SIGNAL MOD. RATE	MASKER CONDITION	LISTENERS' THRESHOLDS		AMOUNT OF MASKING Peripheral	Central
10 Hz	No Masker	LP	-24.5		
		ML	-24.2		
		JL	-25.3		
		MM	-23.1		
		AVG	-24.3		
	1-Tone Fixed	LP	-23.0	1.5	
		ML	-22.7	1.5	
		JL	-22.4	2.9	
		MM	-20.4	2.7	
		AVG	-22.1	2.2	
	1-Tone Random	LP	-23.2		-0.2
		ML	-20.9		1.8
		JL	-22.2		0.2
		MM	-17.6		2.8
		AVG	-21.0		1.1
	10-Tone Fixed	LP	-21.5	3.0	
		ML	-20.8	3.4	
		JL	-20.4	4.9	
		MM	-18.1	5.0	
		AVG	-20.2	4.1	
	10-Tone Random	LP	-20.1		1.4
		ML	-19.3		1.5
		JL	-12.3		8.1
		MM	-11.8		6.3
		AVG	-15.9		4.3

Table 3-2

Amounts of Peripheral and Central Masking for Each Masker Condition When the Signal Was Modulated at 100 Hz

SIGNAL MOD. RATE	MASKER CONDITION	LISTENERS' THRESHOLDS		AMOUNT OF MASKING Peripheral	Central
100 Hz	No Masker	LP	-28.0		
		ML	-24.8		
		JL	-25.7		
		MM	-23.2		
		AVG	-25.4		
	1-Tone Fixed	LP	-24.4	3.6	
		ML	-21.6	3.2	
		JL	-23.9	1.8	
		MM	-20.7	2.5	
		AVG	-22.6	2.8	
	1-Tone Random	LP	-23.9		0.5
		ML	-16.6		5.0
		JL	-19.3		4.6
		MM	-20.0		0.7
		AVG	-20.0		2.6
	10-Tone Fixed	LP	-18.0	10.0	
		ML	-18.6	6.2	
		JL	-9.0	16.7	
		MM	-13.4	9.8	
		AVG	-14.8	10.6	
	10-Tone Random	LP	-7.7		10.3
		ML	-5.3		13.3
		JL	-3.6		5.4
		MM	-3.9		9.5
		AVG	-5.1		9.7

signal is fairly resistant to both peripheral and central masking.

In addition, it should be noted that there were individual differences in the amounts of central masking in the 10-tone condition. Listeners LP and ML had an average of 1.5 dB of masking, whereas listeners JL and MM had an average of 7.2 dB. Thus JL and MM were more affected by masker uncertainty than LP and ML.

When the signal was modulated at 100 Hz (see Table 3-2), a different picture emerges. The average amounts of peripheral masking in the 1- and 10-tone masker conditions were 2.8 and 10.6 dB, respectively. The average amounts of central masking were 2.6 dB in the 1-tone condition and 9.7 dB in the 10-tone condition. All of these masking amounts are larger than what was found when the signal was modulated at 10 Hz. The 100-Hz modulation, therefore, appears to be more susceptible to both peripheral and central masking than the 10-Hz modulation, particularly when the masker is composed of 10 tones.

Discussion of Modulation Rates

The rates of amplitude modulation used in our main experiment were 10 and 100 Hz. These rates were selected because they are probably mediated by different detection processes (Viemeister, 1979). In the case of 10 Hz, detection is best thought of in terms of a temporal process. That is, listeners detect amplitude modulation

by noting that the envelope of the waveform increases and decreases in intensity over time. In the case of 100 Hz, detection can be described in terms of a spectral process. That is, listeners detect the presence of the sidebands to identify an amplitude modulated signal. In the present study, listeners were always better able to detect a slower rate of amplitude modulation in conditions of both peripheral and central masking, particularly for 10-tone maskers.

One explanation for this difference in masking effects on the two rates of modulation is based on the two hypothetical detection processes. There could have been some type of interference between the process by which a modulated signal was detected (i.e., temporal or spectral) and the process invoked by the masker. The masker tones in this study could be spaced no closer than a critical band apart. Thus, the analysis of the maskers presumably would have been in terms of the frequencies of the tones composing them. The maskers, therefore, would most likely activate a spectral process.

If the modulation rate were fast enough for signal detection to be based on a spectral process, then interference by the masker could have resulted. However, if the modulation rate were slow enough for signal detection to be based on a temporal process, then interference by the masker may have been reduced or avoided. In such a case, the signal could have activated

a temporal process and the masker could have activated a spectral process. If these two processes were essentially independent, the result could be reduced interference or masking.

Control Experiment

As mentioned earlier, the masker tones were selected from a wider frequency range for the 10-Hz modulated signal than for the 100-Hz modulated signal. This was done so that the frequency spacing between the sidebands of the signal and the closest possible masker tones would be similar at both modulation rates. A question could be raised, however, regarding what would have happened if we had used the wider frequency range with the 100-Hz modulated signal. To answer this question, we determined two previous listeners' (LP and ML) thresholds for the 10-tone fixed and random conditions using the wider frequency range.

Listeners' thresholds (20 log m) for the five, fixed, 10-tone maskers and the random, 10-tone condition are shown in Figure 3-6. In addition, LP and ML's previous thresholds from the no masker condition are presented for comparison. For the fixed, 10-tone condition, the average threshold for these two listeners was -13.7 dB. Thus, when the masker tones are selected from a wider frequency region approximately 12.8 dB of peripheral masking results. For the random, 10-tone condition, the average

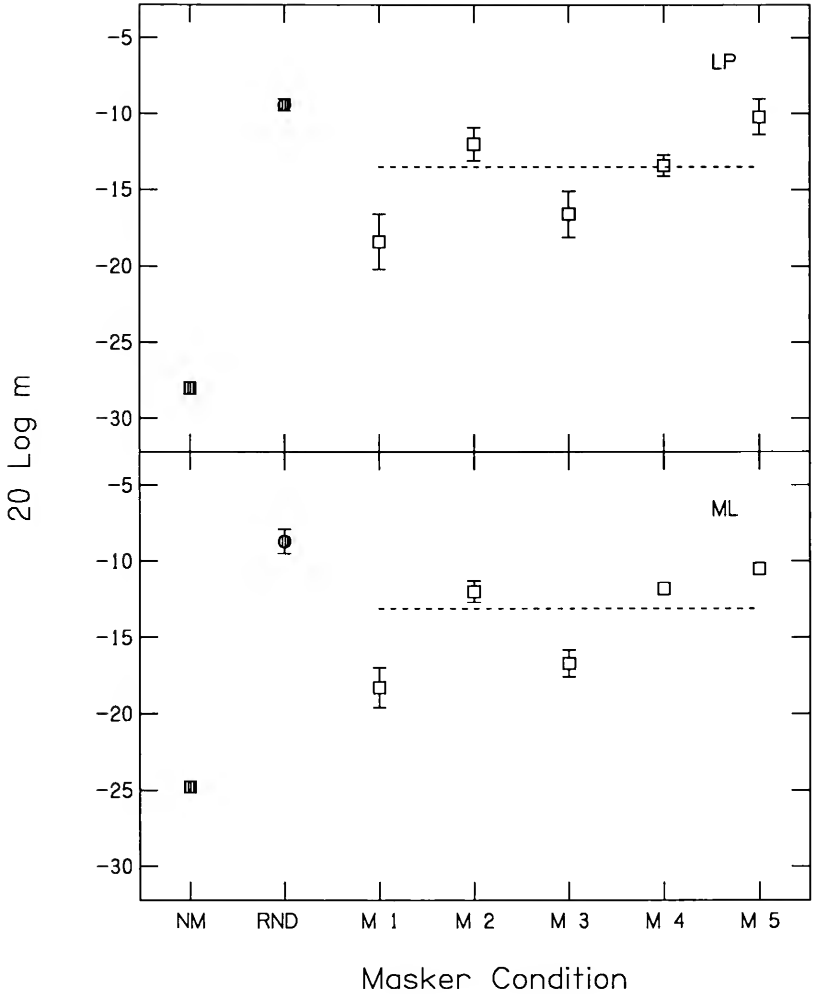


Figure 3-6. Two listeners' thresholds (20 log m) are presented for the 5, 10-tone maskers selected for the fixed condition. Listeners' thresholds are also presented for the no masker (NM) condition and for the 10-tone random masker condition (RND). The dotted horizontal line represents listeners' expected thresholds for the random masker condition.

threshold for these two listeners was -9.1 dB. The difference in thresholds for the fixed and random conditions indicates that there is about 4.6 dB of masking due to masker uncertainty.

In Table 3-3, the present 100-Hz modulation data for the wider frequency range is compared with the 100-Hz modulation data where the frequency range of the masker tones was narrower. Comparing the wider frequency range data (i.e., present data) with the narrower frequency range data (i.e., previous data), the wider frequency range produces approximately 5 dB more peripheral masking than the narrower range. This result is expected because the masker tone energy could be present nearer the signal channel.

The effects of central masking for the two frequency ranges are also different. For the wider frequency range, there was an average of 4.6 dB of masking due to masker uncertainty. For the narrower range, the average amount of masking was 11.8 dB. Although this difference in central masking looks fairly large, it is somewhat deceptive. If we compare the average thresholds for the two random masker conditions (wider and narrower frequency ranges), then the difference is only 2.6 dB. Thus, listeners' performances in the 10-tone random masker conditions were quite similar for both frequency ranges. The difference in central masking seems to be primarily due to the 5 dB difference in the fixed masker conditions.

Table 3-3

Amounts of Peripheral and Central Masking for Each 10-Tone Masker Condition When the Masking Tones Were Selected from the Narrower and Wider Frequency Ranges

SIGNAL MOD. RATE	MASKER CONDITION	LISTENERS' THRESHOLDS		AMOUNT OF MASKING Peripheral	Central
100 Hz	No Masker	LP	-28.0		
		ML	-24.8		
		AVG	-26.4		
	10-Tone Fixed Narrower Range	LP	-18.0	10.0	
		ML	-18.6	6.2	
		AVG	-18.3	8.1	
	10-Tone Fixed Wider Range	LP	-13.5	14.5	
		ML	-13.8	11.0	
		AVG	-13.7	12.8	
	10-Tone Random Narrower Range	LP	-7.7		10.3
		ML	-5.3		13.3
		AVG	-6.5		11.8
	10-Tone Random Wider Range	LP	-9.4		4.1
		ML	-8.7		5.1
		AVG	-9.1		4.6

Summary

The primary purpose of this study was to investigate the effects of central masking on listeners' abilities to discriminate amplitude modulation. We described two methods to estimate the relative contributions of peripheral and central masking. In preliminary work, we

were unable to quantify accurately the masking amounts so we then turned to the subtractive method. We could assess the relative contributions of both peripheral and central masking with the subtractive method. The results indicated that the 100-Hz modulation rate was more susceptible to both peripheral and central masking, particularly for 10-tone maskers.

CHAPTER 4

ACROSS-FREQUENCY INTERFERENCE PRODUCED BY TWO-TONE WAVEFORMS

Introduction

Yost and Sheft (1989) showed that the threshold for amplitude modulation detection was increased (poorer performance) when an amplitude-modulated masker tone was presented simultaneously with the modulated signal. The data were particularly surprising because the signal and masker carrier frequencies were separated by approximately 2 octaves. Yost and Sheft concluded that listeners were unable to completely ignore modulation at a distant frequency and attend only to the modulation at the signal frequency. Because the carrier tones were 2 octaves apart, it is unlikely that peripheral masking was occurring. Thus, these data suggest that there was interference between the envelope of the masker waveform and the envelope of the signal waveform.

We considered several questions related to these findings in our study. Our primary question focused on the type of waveform stimuli used for the signal and masker. First, we attempted to replicate Yost and Sheft's findings using the same amplitude-modulated carriers they employed. Second, we considered a different type of

waveform. We used a two-tone complex that produces a sinusoidal envelope similar to that produced by amplitude modulation. We will discuss the two-tone waveform in more detail later.

The second question of interest was whether or not this interference occurred for different modulation rates. We chose three different modulation rates in this condition.

Our final question concerned the frequency relation between the signal and masker. In Yost and Sheft's work, the signal and masker were multiples of each other. Using the two-tone waveform stimuli, we determined the amount of interference that occurred when the signal and masker frequencies were not multiples of each other. In addition, we explored the effect of a difference in modulation rate between the signal and masker. We held the modulation rate of the signal constant and determined how the amount of interference changed with variation in the masker modulation rate.

Previous Study

In Yost and Sheft's study, the signal and masker were always carrier tones that were amplitude modulated at a rate of 10 Hz. The listener's task was to detect the presence of the amplitude-modulated signal in a 2AFC procedure. In one interval, the modulated signal, a carrier frequency (CF) plus the two sidebands located at

CF +/- 10 Hz, was presented. In the other interval, an unmodulated tone of the same carrier frequency was presented. In both intervals, the same modulated masker was presented simultaneously. Thresholds were determined as the depth of modulation (20 log m) necessary to estimate the 70.7% point on the psychometric function.

Yost and Sheft compared two frequency conditions. In one condition, the signal was at 1000 Hz and the masker was at 4000 Hz. In the other condition, the signal and masker frequencies were reversed. For both conditions, the modulated signal was always more difficult to detect in the presence of the modulated masker. The amount of interference due to the masker was approximately 15 dB for the 1000 Hz signal, and 9 dB for the 4000 Hz signal.

Waveform Stimuli

Since the rate of modulation (10 Hz) is relatively slow, it is best understood in terms of a temporal process. Thus, the important cue for detection is the fluctuations of the waveform's envelope over time. Yost and Sheft's work suggests, then, that processing temporal information at one frequency location can interfere with the processing of similar temporal information at a distant frequency location.

We wanted to determine if temporal interference occurs with a different type of waveform. In our study, we used two-tone complexes, where the frequency separation

between the two tones was small. Two tones close in frequency produce "beats" at a rate equal to their frequency separation. That is, the envelope of the two-tone combination fluctuates over time like the envelope of an amplitude-modulated tone. Throughout the remainder of this chapter, we will often refer to the two-tone waveform as the "beating" waveform.

Figure 4.1 illustrates the similarity in the envelope fluctuations for a beating waveform and amplitude-modulated waveform. The top waveform is two tones that are separated in frequency by 10 Hz (i.e., beating waveform), thus their envelope fluctuates at a rate of 10 Hz. The bottom waveform is a carrier tone that is amplitude-modulated at a rate of 10 Hz, thus its envelope fluctuates at a rate of 10 Hz. Although there are some differences in detail between the two waveforms, they both provide the same temporal information (i.e., their envelopes are exactly sinusoidal (AM) and nearly sinusoidal (two-tone), and their rate of fluctuation is 10 Hz).

General Procedure

Two, normal-hearing listeners participated in this study. Both of the listeners were college students recruited through advertisements placed in the student newspaper. They were paid at an hourly rate for their

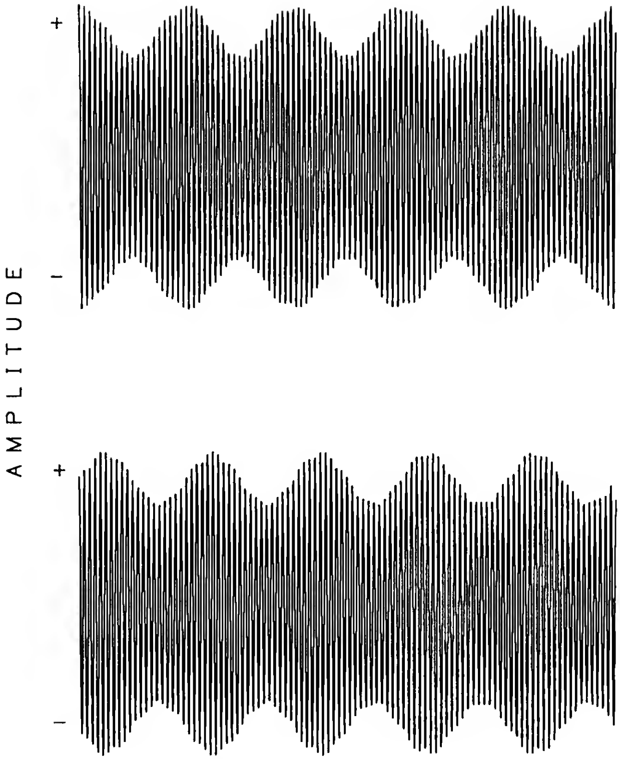


Figure 4-1. The top waveform illustrates two tones that are separated in frequency by 10 Hz (i.e., beating waveform). The bottom waveform illustrates a carrier tone that is amplitude modulated at a rate of 10 Hz.

participation. Each of the listeners received several hours of practice prior to data collection.

The observers were seated in individual, sound-treated rooms. The stimuli were presented diotically over Sennheiser HD 414 SL earphones, and both phones were driven in-phase. All the stimuli were generated digitally, played over D/A's at a sampling rate of 14,286 Hz, and low-pass filtered at 6,000 Hz. The duration of the stimulus was 440 msec, including 20-msec $\cos^2$ rise/decay ramps.

In each condition of this study, listeners were asked to detect the presence of envelope modulation in 2AFC trials. Two types of waveforms were used as signals. For some conditions, the signal was a beating waveform and for other conditions, the signal was an amplitude-modulated waveform. As was described previously, both types of signals have sinusoidal envelopes that fluctuate at a particular rate. We will refer to the frequency of fluctuation as the envelope modulation rate.

In addition, in both the signal and nonsignal trial intervals, a masker was presented simultaneously. The same masker was used for a block of trials. Two types of maskers were also used, either a beating or an amplitude-modulated waveform. By pairing each signal type with each masker type, a total of four conditions were possible. Each condition of the study, therefore, will be described in terms of the signal type and masker type (i.e.,

amplitude-modulated signal (S_{AM}) and amplitude-modulated masker (M_{AM}), beating signal (S_B) and beating masker (M_B), beating signal (S_B) and amplitude-modulated masker (M_{AM}), amplitude-modulated signal (S_{AM}) and beating masker (M_B)).

For each block of trials, the depth of envelope modulation was varied using an adaptive procedure (Levitt, 1971). A 2-down, 1-up procedure was used to estimate listeners' thresholds that corresponded to 70.7% correct detection. Following two correct responses, the level of the signal was decreased. Following one incorrect response, the level of the signal was increased. The initial stepsize was 4 dB, and after 4 "reversals" the stepsize was reduced to 2 dB. Trials were run in blocks of 50 and each run produced approximately 14 reversals. Thresholds were determined by averaging the signal level across the last even number of reversals, excluding the first four reversals.

The signal level was varied differently depending on the type of signal. If the signal was an amplitude-modulated tone, then the depth of modulation (20 log m) was varied. If the signal was beating tones, then the amplitude of one of the tones was varied relative to the amplitude of the second tone. Although the signal level was varied differently for each signal, the variation preserved the peak-to-valley or max/min ratio of the envelope. That is, for a given signal level the max/min

ratio of the envelopes was the same for both the amplitude-modulated tone and beating tone waveforms.

On each stimulus presentation, the overall level of the stimulus was chosen, at random, from a 20-dB range in 1-dB steps. The median stimulus level was 70 dB SPL. This random level procedure was used to reduce the possibility that listeners used changes in overall stimulus level as a cue for the detection of envelope modulation.

In the next section of this chapter, we will focus on the specific questions related to across-frequency interference. First, what effect does the type of waveform have on interference? We will describe our attempt to replicate the findings of Yost and Sheft (1989). Then we will determine whether across-frequency interference occurs with a beating waveform. Second, we will focus on the question of whether interference occurs for different rates of modulation. Third, we will consider the frequency relation between the signal and masker locations. Finally, we will determine how interference depends on the difference in modulation rate of the signal and masker.

Results and Discussion

Across-Frequency Interference

First, we attempted to replicate Yost and Sheft's findings. In this condition, both the signal and masker

were amplitude-modulated tones. We compared two frequency conditions, as Yost and Sheft did. In one condition, the signal was at 1000 Hz and the masker was at 4000 Hz. In the other condition, the signal and masker frequencies were reversed. In both conditions, the envelope modulation rate was 10 Hz for both the signal and masker.

Listeners' average thresholds for the detection of the amplitude-modulated signal (S_{AM}) alone and when the signal was presented with an amplitude-modulated masker (M_{AM}) are shown in Table 4-1. The difference in the two thresholds (i.e., signal alone minus signal plus masker) represents the amount of interference due to the presence of the modulated masker.

For these conditions, we found 13.6 and 8.0 dB of interference when a modulated masker was presented with a 1000 and 4000 Hz signal, respectively. These data are similar to the results reported by Yost and Sheft (1989). They found approximately 13 and 9 dB of interference in the comparable conditions. From these data, we too conclude that the detection of a modulated signal is more difficult when a modulated masker is present at a distant frequency.

After replicating the finding that across-frequency interference occurs between two amplitude-modulated tones, we turned our attention to the next question. Does this type of temporal interference occur with beating tones? In this condition <u>both</u> the signal and masker were beating

Table 4-1

Listeners' Average Thresholds (20 log m) for the Detection of an Amplitude-Modulated Signal (SAM) When It Was Presented Alone, and With an Amplitude-Modulated Masker (MAM). The Envelope Modulation Rate Was 10 Hz for Both the Signal and Masker.

SIGNAL (S_{AM})	MASKER (M_{AM})	LISTENERS' THRESHOLDS		AMOUNT OF INTERFERENCE
1000 Hz	None	LP	-26.1	
		CB	-23.4	
		AVG	-24.8	
1000 Hz	4000 Hz	LP	-12.4	13.7 dB
		CB	-9.9	13.5 dB
		AVG	-11.2	13.6 dB
4000 Hz	None	LP	-26.9	
		CB	-24.3	
		AVG	-25.6	
4000 Hz	1000 Hz	LP	-19.5	7.5 dB
		CB	-15.7	8.5 dB
		AVG	-17.6	8.0 dB

waveforms. Again we ran the two frequency conditions described in the replication of Yost and Sheft's work. In this condition, one tone of the two-tone complex was located at either 1000 or 4000 Hz. The second tone of the complex was always 10 Hz above that frequency and hence produced an envelope fluctuation of 10 Hz.

Listeners' average thresholds for detecting the presence of a beating signal (S_B) alone and when the signal was presented with a beating masker (M_B) are presented in Table 4-2. The difference in the two thresholds represents the amount of interference due to the presence of the masker.

Table 4-2

Listeners' Average Thresholds for the Detection of a Beating Signal (SB) When It Is Presented Alone, and With a Beating Masker (MB). The Envelope Modulation Rate Was 10 Hz for Both the Signal and Masker.

SIGNAL (S_B)	MASKER (M_B)	LISTENERS' THRESHOLDS		AMOUNT OF INTERFERENCE
1000 Hz	None	LP	-25.7	
		CB	-24.8	
		AVG	-25.2	
1000 Hz	4000 Hz	LP	-20.2	5.5 dB
		CB	-16.9	7.9 dB
		AVG	-18.9	6.3 dB
4000 Hz	None	LP	-24.9	
		CB	-21.6	
		AVG	-23.2	
4000 Hz	1000 Hz	LP	-14.5	10.4 dB
		CB	-16.2	5.4 dB
		AVG	-15.4	7.8 dB

For this condition, we found 6.3 and 7.8 dB of interference when a beating masker was presented with a 1000 and 4000 Hz signal, respectively. The amount of interference when the signal is 1000 Hz is approximately one-half what is was in the amplitude-modulation condition (shown in Table 4-1). The amount of interference when the signal is 4000 Hz is about the same for both the beating and amplitude-modulation conditions.

We conclude from these data that the across-frequency interference does occur with a beating waveform. The decrease in the amount of interference from the amplitude-modulation condition is not completely understood. Listeners first completed amplitude-modulation condition and then the beating condition. One possibility is that the improvement in performance is due to practice. However, the similar amounts of interference for both signal frequencies found in the beating condition do seem more sensible. It is unclear why such asymmetries would occur in the amplitude-modulation condition.

In addition to using the same type of waveform for both the signal and masker, we compared conditions where the waveform type was not the same for the signal and masker. That is, in one condition the signal was a beating waveform and the masker was an amplitude-modulated waveform and in the other the condition the waveform types were reversed. Listeners' average thresholds are presented in Table 4-3. Note that the signal was always

located at 1000 Hz and the masker was always located at 4000 Hz. The envelope modulation rate was always 10 Hz for both the signal and masker.

We found that an amplitude-modulated masker produced 9.8 dB of interference when listeners were trying to detect a beating signal. In contrast, a beating masker produced 12.5 dB of interference when listeners were

Table 4-3

Listeners' Average Thresholds for the Signal Alone Conditions and the Signal Plus Masker Conditions. The Signal Frequency Was 1000 Hz and the Masker Frequency Was 4000 Hz. The Envelope Modulation Rate Was 10 Hz for Both the Signal and Masker.

SIGNAL	MASKER	LISTENERS' THRESHOLDS	AMOUNT OF INTERFERENCE
S_B	None	LP -25.7	
		CB -24.8	
		AVG -25.2	
S_B	M_{AM}	LP -15.5	10.3 dB
		CB -15.3	9.6 dB
		AVG -15.4	9.8 dB
S_{AM}	None	LP -26.1	
		CB -23.4	
		AVG -24.8	
S_{AM}	M_B	LP -13.6	12.5 dB
		CB -10.9	12.5 dB
		AVG -12.2	12.5 dB

trying to detect an amplitude-modulated signal. These waveform combinations for the signal and masker produced more interference than when the signal and masker were both beating waveforms (6.3 dB of interference), and similar amounts as when both were amplitude-modulated waveforms (13.6 dB of interference).

Increase in Modulation Rate for Both Signal and Masker

In this section, we will address the question of whether or not across-frequency interference occurs when the rate of envelope modulation is increased for both the signal and masker. As previously discussed, the detection of envelope modulation is based on a temporal process for slow rates and on a spectral process for faster rates. If the interference is the result of a conflict in temporal information, then we would expect the amount of interference to decrease with an increase in modulation rate. This would be the expected outcome because the spectral process results in frequency information being coded in separate channels and interference between distant frequency channels would be unlikely.

We completed the modulation rate condition for the four possible combinations of signal and masker waveform type. For each combination, the signal and masker both had the same envelope modulation rate. Previously we determined listeners' thresholds for a slow envelope modulation rate of 10 Hz. In this section, we determined

listeners' thresholds for a fast modulation rate of 160 Hz (detection based on a spectral cues) and an intermediate rate of 40 Hz. In all conditions, the signal was located at 1000 Hz and the masker was located at 4000 Hz.

In each condition, thresholds were similar across listeners. Thus, to simplify the data presentation, a summary of the results will be presented rather than individual listeners' thresholds. The interference amounts for each waveform condition and envelope modulation rate are listed in Table 4-4. The interference amounts were determined as in previous tables (i.e., signal alone minus signal plus masker). For ease of comparison, the 10-Hz data previously discussed are also included.

Table 4-4

Average Amounts of Interference (dB) for Each Waveform Condition and Envelope Modulation Rate. The Signal Frequency Was 1000 Hz and the Masker Frequency Was 4000 Hz.

SIGNAL/MASKER CONDITION		ENVELOPE MODULATION RATES 10 Hz	40 Hz	160 Hz
AM/AM		13.6	7.0	11.7
BEAT/BEAT		6.7	8.2	7.5
BEAT/AM		9.3	9.3	8.8
AM/BEAT		12.5	6.0	8.3
	AVG	10.5 dB	7.6 dB	9.1 dB

It appears from the data that our expectation of a decrease in the interference amount with an increase in modulation rate was not fulfilled. One possible problem may be that we did not increase the envelope modulation to a high enough rate. As the results discussed in Chapter 5 will indicate, it is possible that a rate of 320 Hz may be necessary for detection to be based primarily on spectral cues.

Frequency Relation Between Signal and Masker

As we mentioned, Yost and Sheft (1989) used frequencies for their signal and masker that were multiples of each other. In this condition we used approximately the same frequency separation they used, but the frequencies of the signal and masker were not multiples. The signal, in this condition, was located at 790 Hz and the masker was located at 3127 Hz. We looked at two conditions, one where both the signal and masker were beating waveforms, and a second where the signal was a beating waveform and the masker was an amplitude-modulated waveform. In both conditions, the envelope modulation rate of the signal and masker was 10 Hz. Again, we will present a summary of the results. The average interference amounts for each waveform condition are indicated in Table 4-5.

When the signal was a beating waveform, an average of 6.4 and 6.8 dB of interference resulted from the presence

Table 4-5

Average Interference Amounts for the Beating Signal and Masker Condition, and the Beating Signal and Amplitude-Modulated Masker Condition. The Signal Frequency Was 790 Hz and the Masker Frequency Was 3127 Hz.

SIGNAL/MASKER CONDITION	AMOUNT OF INTERFERENCE
BEAT/BEAT	6.4 dB
BEAT/AM	6.8 dB

of a beating masker and an amplitude-modulated masker, respectively. Previously, when the signal was at 1000 Hz and the masker was at 4000 Hz, we found 6.3 and 9.3 dB of interference for the same two conditions. These data suggest that masker interference is not limited to conditions where the signal and masker frequencies are multiples of each other.

Increase in Masker Modulation Rate

In an earlier experimental condition, we found no systematic decrease in the amount of interference as the envelope modulation of both the signal and masker was increased. Now we turn our attention to a slightly different question regarding envelope modulation rate. We explored how the amount of interference changed with variation in the masker modulation rate, while holding the signal modulation rate constant.

In this condition, the signal was always a beating waveform with an envelope modulation rate of 10 Hz. Modulation rates of 20, 40, and 80 Hz were completed for both a beating and an amplitude-modulated masker. The signal frequency was 790 Hz and the masker frequency was 3127 Hz. The averaged (across listeners) amounts of interference at each modulation rate for the beating and amplitude-modulated masker conditions are shown in Figure 4-2.

We would expect that as the envelope modulation rate of the maskers was increased the amount of interference would decrease. From the data, this expectation appears to be supported for modulation rates greater than 20 Hz. Comparing the 10 and 20 Hz modulation rates, the maskers produce the same average amount of interference. This suggests that detection process of envelope modulation is not sharply tuned. These results agree with interference data reported for an amplitude-modulated tone probe and masker (Yost, Sheft, and Opie, 1989) and an amplitude-modulated, broadband noise signal and masker (Bacon and Grantham, 1989). Both studies indicated there was a decrease in the amount of interference when the signal/probe and masker were modulated at different rates, but for a given masker frequency there appeared to be "spread of masking."

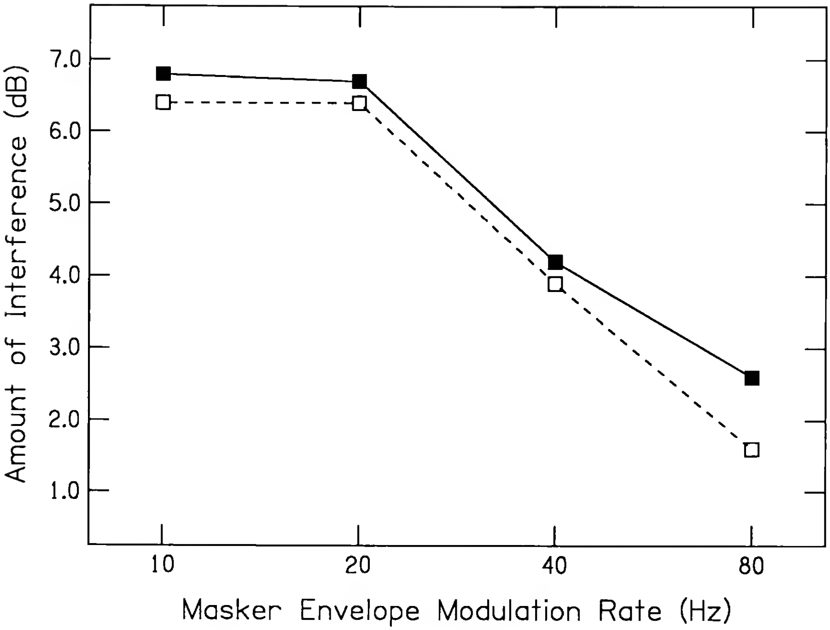


Figure 4-2. The averaged amounts of interference (dB) are presented for each masker envelope modulation rate. Two masker conditions are shown: beating (open squares) and amplitude-modulated (solid squares).

Summary and Conclusions

In this study, we investigated several aspects of the across-frequency interference demonstrated by Yost and Sheft (1989). For amplitude-modulated carriers that were 2 octaves apart, Yost and Sheft found that a signal was more difficult to detect when presented simultaneously with a masker. We first replicated these results and then considered a different type of stimulus, a beating waveform. We, too, found interference between a beating signal and a beating masker that were quite distant in frequency. It is unlikely that the basis of this interference is peripheral masking given the frequency separation between the signal and masker. Thus, the data for modulated and beating stimuli suggest that there is interference between the envelopes of the signal and masker.

The envelope modulation rate of the signal and masker in all of this work was 10 Hz. The detection of a slow rate of modulation, such as 10 Hz, is based on temporal cues. One possible basis of the interference between the signal and masker is a conflict in the temporal information provided by each waveform. To test this possibility, we compared the amount of interference that occurred for several modulation rates. The results indicated that interference was not limited to a slow rate of modulation. We found that it occurred with a fast modulation rate of 160 Hz.

A second possible basis of the interference was the multiplicative relation between the signal and masker carrier frequencies. In separate conditions, we used carrier frequencies that had approximately the same frequency separation as previous conditions, but that were not multiples of each other. Again, we found interference between the signal and masker.

Finally, we were interested in determining how the amount of interference changed as a function of the masker envelope modulation rate. We held the envelope modulation rate of the signal constant and varied the rate of the masker. In this condition, we expected that as the rate of the masker was increased, the amount of interference would decrease. Once the masker rate was greater than twice the signal rate, the results supported this expectation. This finding suggests that the detection of envelope modulation is not a sharply tuned process.

CHAPTER 5

THE DETECTION OF CHANGES IN AMPLITUDE-MODULATION RATE

Introduction

The purpose of this study was to investigate listeners' abilities to discriminate a change in amplitude-modulation rate. Specifically, we presented two amplitude-modulated carriers sequentially and asked listeners to indicate which one had the slower modulation rate. We were interested in answering three questions.

First, what effect does carrier frequency have on rate discrimination? Zwicker (1952) investigated listeners' abilities to detect the presence of amplitude modulation, for modulation rates ranging from 1 to 6000 Hz, with 250-, 1000- and 4000-Hz carriers. On each trial, listeners had to compare two intervals, one containing a modulated carrier and one containing an unmodulated carrier of the same frequency. He found that for the slower modulation rates, thresholds for detecting the presence or absence of modulation were similar across carrier frequency.

Buus (1983) used two-tone complexes to investigate detection of a change in modulation rate (i.e., envelope frequency). Thresholds were defined as the just

noticeable increase in frequency separation and were measured for frequency separations ranging from 25 to 2560 Hz, depending on the center frequency. He compared four center frequencies: 500, 1000, 2000, and 4000 Hz. Results indicated that, for each center frequency, thresholds fell into two groups. The thresholds were significantly smaller at the narrower frequency separations (slower modulation rates) than at the wider frequency separations (faster modulation rates).

Second, what is the effect of varying the type of spectral cues that are available to listeners? Previous studies using amplitude-modulated noise (Viemeister, 1979) and two-tone complexes (Buus, 1983) have shown a decrease in listeners' performances as modulation rates increase beyond 60 Hz. In both studies, spectral cues were minimized by the choice of waveforms. The long-term power spectrum of sinusoidally, amplitude-modulated, broad-band noise is uniform and invariant across modulation frequency. Therefore, listeners presumably cannot base modulation detection on spectral cues (Viemeister, 1979). In Buus' (1983) two-tone experiment, spectral cues were minimized by changing the frequencies of <u>both</u> tones to produce a desired change in modulation rate (envelope frequency). Spectral cues were minimized because the change in the frequency of each tone was small relative to their pure-tone just noticeable differences. Therefore,

in both studies, performance was poorer at the faster modulation rates.

Schodder and David (1960), using a two-tone complex, asked listeners to indicate whether the pitch increased or decreased when the frequency of the lower tone was decreased. If listeners were attending to the lower tone, then their response to the question of pitch would have always been lower. However, if listeners were attending to the envelope frequency of the tone complex, their response to the question of pitch would have always been higher. Schodder and David found that when there was a small frequency separation between the two tones, listeners attended to the envelope rate. In contrast however, when the frequency separation was larger, listeners attended to the lower frequency tone of the two-tone complex.

In this study, we used amplitude-modulated tonal carriers. At faster modulation rates, we expected that listeners could no longer use a temporal cue (i.e. envelope fluctuation rate) and would have to rely on spectral cues (i.e., resolution of the sidebands of the carrier). We used three spectral cue conditions and they will be explained later.

Third, and finally, what is the effect of the depth of modulation on modulation rate discrimination? We used two depths of modulation. Reduction of the depth of modulation reduces the amplitude of the sidebands and,

presumably, should make it more difficult to detect a change in sideband frequency. Therefore, we expected to find more differences across modulation depth for the faster modulation rates than for the slower rates.

General Procedure

A total of three, normal-hearing listeners participated in the experiment. All the listeners were college students recruited through advertisements placed in the student newspaper. They were paid at an hourly rate for their participation. Each of the listeners received several hours of practice prior to data collection.

Observers were seated in individual, sound-treated rooms. The stimuli were presented diotically over Sennheiser HD 414 SL earphones, and both phones were driven in-phase. All the stimuli were generated digitally, played over D/A's at a sampling rate of 10,000 Hz, and low-pass filtered at 5,000 Hz. The duration of the stimulus was 800 msec, including 10-msec $\cos^2$ rise/decay ramps.

The same task was used in each condition of the experiment. Listeners were asked to discriminate which of two amplitude-modulated carriers had the lower envelope frequency. A carrier that was amplitude modulated by a slower, standard modulation rate and a carrier that was amplitude modulated by a faster, comparison modulation

rate were presented in 2AFC trials. The standard modulation rate was held constant across a block of trials. Six standard modulation rates were used, they were 10, 20, 40, 80, 160, and 320 Hz.

On each trial the comparison modulation rate was determined as follows:

$$20 \log f_m = 20 \log f_s + 20 \log f_m/f_s,$$
$$20 \log f_m/f_s = \alpha, \tag{5.1}$$

where f_m was the modulation rate of the comparison, f_s was the modulation rate of the standard, and α was a constant. On this logarithmic scale of frequency, we increased or decreased the comparison rate ($20 \log f_m$) by an equal amount, α. Initially α was 4, then after 4 reversals, we set α to 2. For each block of trials, the comparison modulation rate was varied using an adaptive procedure (Levitt, 1971). A 2-down, 1-up procedure was used to estimate listeners' thresholds that corresponded to 70.7% correct performance. The frequency of the comparison modulation was decreased after two correct responses. The frequency of the comparison modulation rate was increased after one incorrect response. Trials were run in blocks of 50 and each block produced approximately 14 reversals. Thresholds were determined by averaging the last even number of reversals, excluding the first four reversals. Thresholds will be presented as the difference between the standard and comparison modulation rates (Δf), or the

difference between the standard and comparison modulation rates divided by the standard modulation rate ($\Delta f/f$).

The median level of the stimulus was 70 dB SPL. On each presentation, the overall level of the stimulus was chosen, at random, from a 10-dB range in 1-dB steps. This random level procedure was used to reduce the possibility of listeners using the stimulus level as a cue in any of their decisions.

Method

Carrier Frequency

Four carrier frequencies, 516, 1006, 2025, and 4008 Hz, were used in this condition. The depth of modulation was 100% (20 log m = 0). On each trial, the same carrier frequency was used for both the standard and comparison modulation rates. We will later refer to this condition as the fixed carrier condition.

Results and discussion

Individual listeners' thresholds for each carrier frequency are shown in Figure 5-1 as a function of the standard modulation rate. For each carrier frequency, listeners TM (squares) and UE (circles) appear to have very similar thresholds across standard modulation rates. Although listener CB (triangles) has the same pattern of results, performance is consistently poorer than that of the other two listeners.

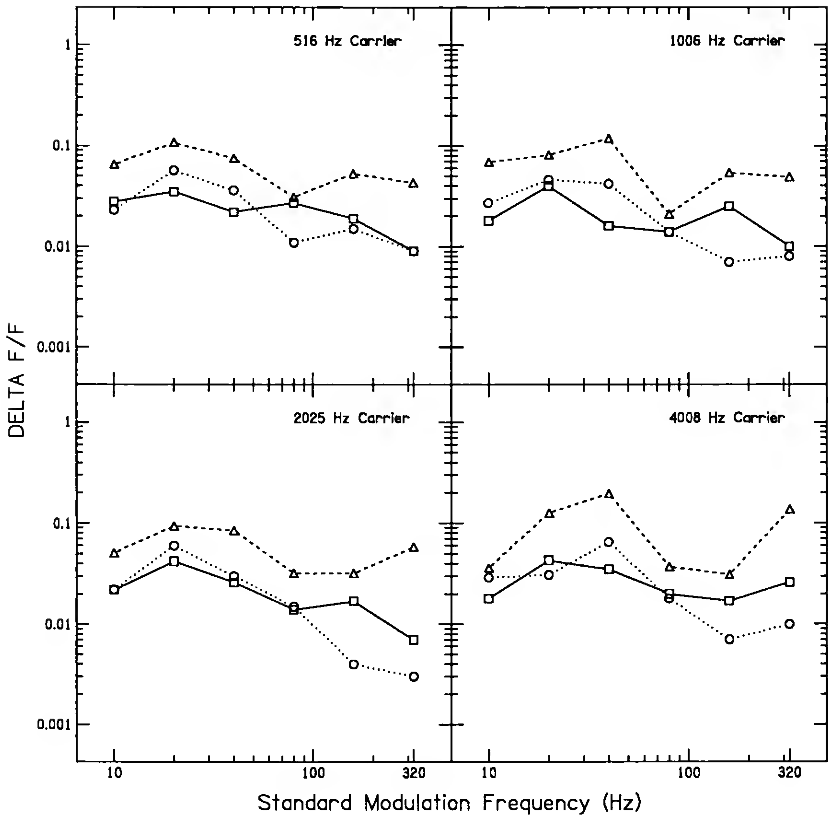


Figure 5-1. Thresholds for three listeners (TM, squares; UE, circles; and CB, triangles) are presented for each carrier frequency as a function of the standard modulation frequency.

Figure 5-2 shows the fixed carrier thresholds (averaged across subjects) for each of the four carrier frequencies as a function of standard modulation rate.The pattern of results is similar across the four carrier frequencies. For the slower modulation rates (i.e., 10, 20, and 40 Hz), listeners' thresholds are relatively constant or show a slight increase with increasing modulation rate. For the faster modulation rates (i.e., 80, 160, and 320 Hz), thresholds generally appear to be slightly lower (better performance) than the slower modulation rates. In addition, at each standard modulation rate the thresholds are quite similar across carrier frequency. From these data, we conclude that there is little or no effect of carrier frequency when the same carrier is used for both the standard and comparison modulation rates.

A comparison of the fixed carrier data and the results of an envelope discrimination study reported by Buus (1983) is shown in Figure 5-3. Unlike the previous three graphs, the data are presented as Δf. Although Buus' procedure was somewhat different from ours, there is good agreement where the two sets of data overlap.

Spectral Cue

In the data we have just discussed, the same carrier frequency was used for both the standard and comparison

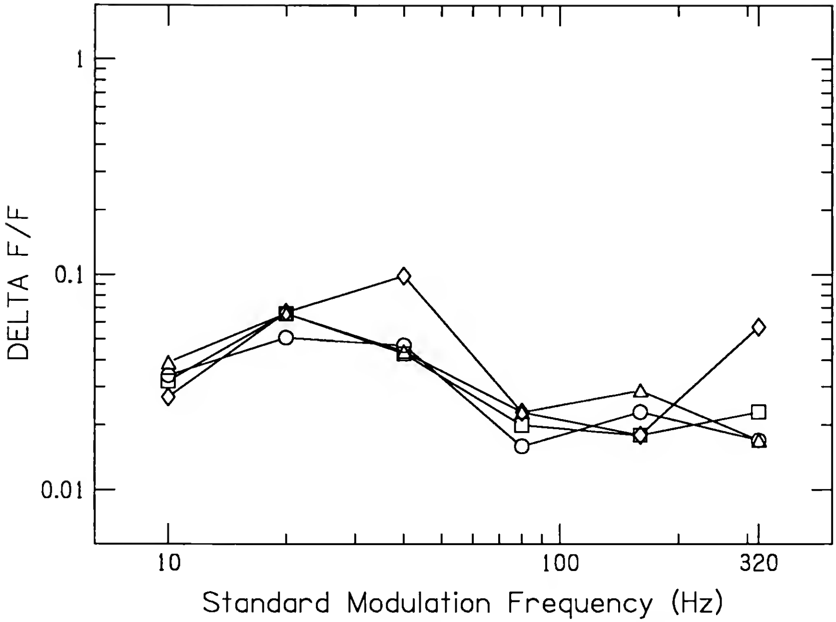


Figure 5-2. Same data as shown in Figure 5-1, averaged across the three listeners. Four carrier frequencies are shown: 500 (triangles), 1006 (circles), 2025 (squares), and 4008 (diamonds) Hz.

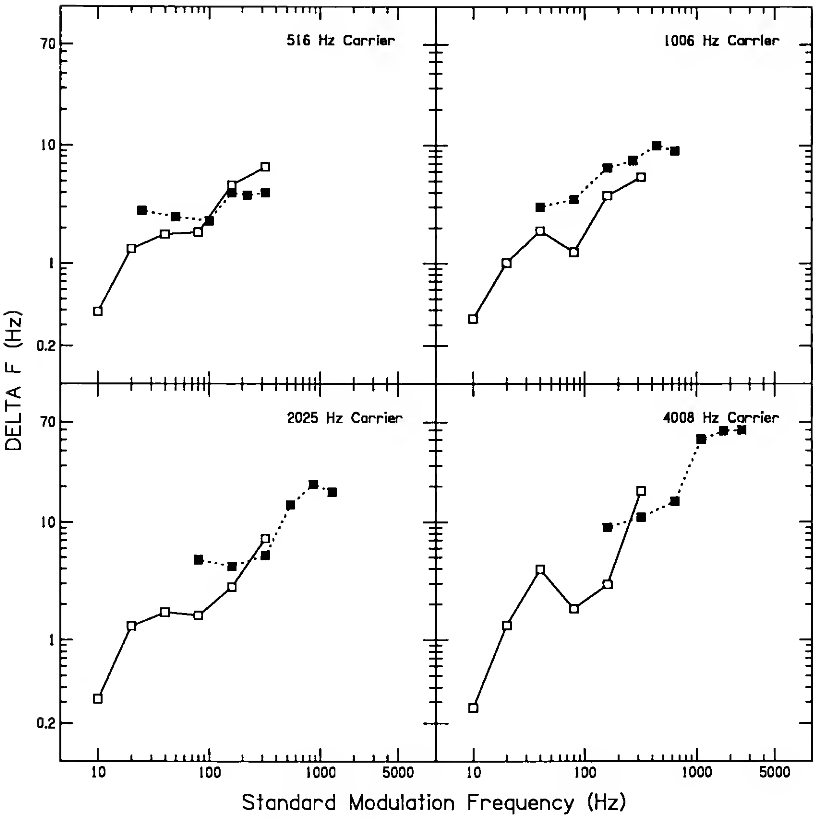


Figure 5-3. Open squares represent same data as shown in Figure 5-2, except presented as delta f. Solid squares are data reported by Buus (1983) for similar conditions.

modulation rates across a block of trials. We call this the fixed carrier condition.

In the random carrier condition, two different carriers were used on each trial, one for the standard modulation rate and one for the comparison modulation rate. The two carrier frequencies were selected from two regions centered around a specified frequency that we will refer to as the center frequency. In this condition, the center frequencies were approximately 500, 1000, 2000, and 4000 Hz. They were actually a few cycles off these values to avoid producing a harmonic sequence when the carrier was modulated. One of the four center frequencies was used for each block of trials. The random carrier selection process will be described next.

On each trial, one carrier frequency was selected from a region beginning 1/6th of an octave above (higher frequency) the center frequency and one carrier frequency was selected from a region beginning 1/6th of an octave below (lower frequency) the center frequency. The widths of the two frequency regions were defined for each of the six standard modulation rates as one half of the standard modulation rate. It should be noted that the 320-Hz standard modulation rate was not used with the 516-Hz carrier in this condition because it was possible for the lower frequency sideband to become inaudible. The modulation rate, either standard or comparison, for the two random carriers was determined randomly on each trial.

Two different carriers, one for the standard modulation rate and one for the comparison modulation rate, were used on each trial in the harmonic carrier condition. For a given modulation rate, either standard or comparison, the carrier frequency was selected randomly from the frequency range 500-4000 Hz. The only restriction on the carrier frequency was that it must be a <u>harmonic</u> of its corresponding modulation rate. Also, the same frequency could not be selected for both carriers on any one trial.

<u>Results and discussion</u>

The fixed carrier condition (previously presented in Figure 5-2) is compared with the other two carrier conditions, random and harmonic, in Figure 5-4. The pattern of results is similar for each carrier/center frequency. At the slower modulation rates (i.e., 10, 20, and 40 Hz), the three conditions produce similar thresholds. At the faster modulation rates (i.e., 80, 160, and 320 Hz), a different picture emerges. Performance in the random carrier condition is consistently poorer than performance in either fixed or harmonic carrier conditions. Performance is slightly better in the fixed condition, relative to the harmonic condition, for the 80- and 160-Hz modulation rates. At the fastest rate of modulation, 320 Hz, this trend reverses. Performance in the harmonic condition is equal to or better than the performance in the fixed condition.

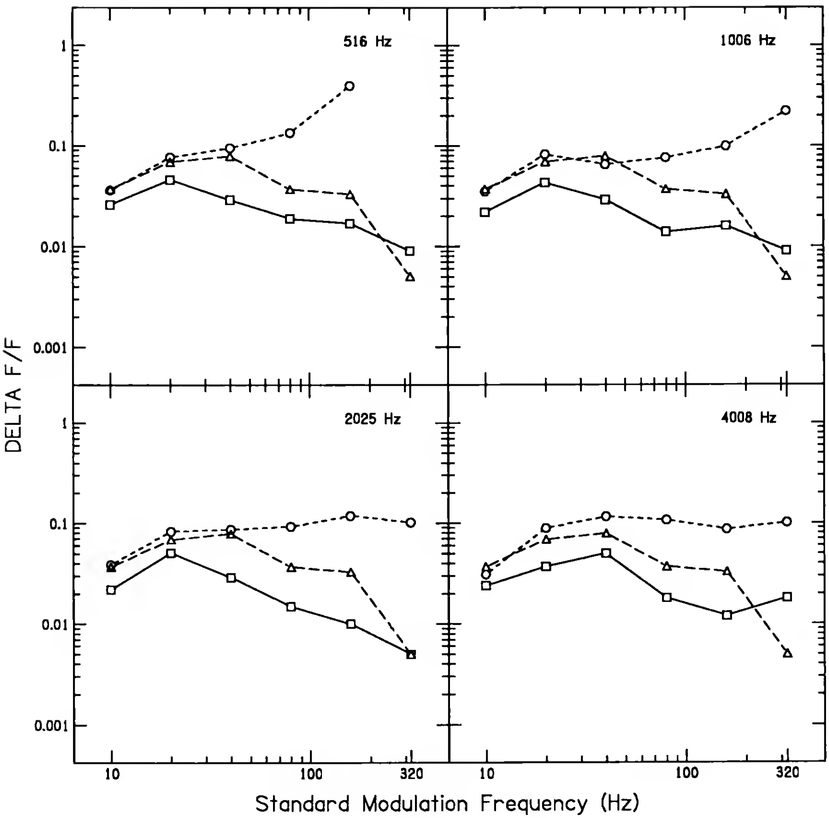


Figure 5-4. Thresholds averaged across three listeners for each carrier/center frequency are presented as a function of the standard modulation frequency. Three carrier conditions are shown: random (circles), harmonic (triangles), and fixed (squares) previously shown in Figure 5-2.

Next, we will consider these similarities and differences in the carrier conditions in terms of the temporal and spectral explanations of amplitude-modulation discrimination.

As was discussed in the Introduction, rate discrimination at the lower modulation rates (i.e., 10, 20, and 40 Hz) is best understood in terms of a temporal process. The important cue for discrimination, then, is the envelope fluctuation over time. Thus, the fixed or random nature of the carrier frequency would seem to be relatively unimportant in the discrimination of a change in envelope rate. The data agree with this belief. At the standard modulation rates of 40 Hz and below, there was little or no differences in thresholds across carrier conditions.

At faster modulation rates (i.e., 80, 160, and 320 Hz), discrimination is best understood in terms of spectral cues. In this case, the important cue for discrimination is a change in the frequencies of the sidebands. When a carrier is modulated by the slower standard modulation rate the frequency separation between the carrier and sidebands will be smaller than when a carrier is modulated by the faster comparison rate. For two carriers having the same frequency, discrimination could be based on a comparison between the absolute frequencies of the sidebands. For two carriers having different frequencies, a direct comparison of the sideband

frequencies would not be possible. Rather, a more difficult comparison between the frequency separations of the carriers and their sidebands in each interval would have to be made. Thus, the fixed or random nature of the carrier frequency would seem to be important when the discrimination of modulation rate is spectrally based. Because performance with the fixed carrier was better than the performance with the random carriers (except for the 320 Hz condition which we will discuss), we conclude that the absolute comparison between the sideband frequencies in the two trial intervals provided the most likely cue for discrimination at the faster modulation rates.

A second possible discrimination cue at faster modulation rates could be pitch. As modulation rates increase, the frequency separation between the carrier and two sidebands also increases and the 3-tone complex may have a weak, but perceptible pitch. Of the three carrier conditions, pitch would have been most reliable as a cue in the harmonic condition, because the carrier was always chosen to be a harmonic of the modulation rate. As a result, the standard and comparisons would always have a pitch equal to their corresponding modulation rates. On a given trial then, the pitch associated with the standard would be lower than the pitch associated with the comparison. In the fixed and random conditions, where the carrier was not a harmonic of the modulation rate, pitch

would not have been a reliable cue due to pitch shift which we will describe next.

Although the carriers were not harmonics of the modulation rate in the fixed and random conditions, the 3-tone complexes could still have a pitch. The actual pitch of those complexes, however, was not equal to the modulation rate as in the harmonic condition. Instead it was shifted, either higher or lower, relative to the pitch of the modulation rate. What could happen as a result of these shifts was that the slower standard could have a pitch equal to or higher than the faster comparison. These pitch shifts made pitch an ambiguous cue in both the fixed and random conditions.

Looking back at the data presented in Figure 5-4, performance in the harmonic condition was better than the performance in the random condition, at all standard modulation rates. Performance in the harmonic condition was only slightly poorer than the fixed condition at 80 and 160 Hz modulation rates, and was equal to or better at 320 Hz modulation rate. Thus we conclude that pitch, too, could be used as a cue for the discrimination of amplitude modulation rate.

Depth of Modulation

Three modulation depths, defined in terms of 20 log m, were used. They were 0, -10, and -20 which correspond to 100, 31.6, and 10% amplitude modulation, respectively.

For each modulation depth, thresholds were determined as a function of four carrier frequencies and the six standard modulation rates. The carrier frequency was always the same for both the standard and comparison modulation rates, across a block of trials (as in the fixed carrier condition). We used the same carrier frequencies used in the previous fixed carrier condition.

The threshold for amplitude-modulation detection at slower modulation rates (64 Hz and below) is at worst $20 \log m = -25$ dB (Zwicker, 1952). This value corresponds to a depth of modulation of approximately 6%. In Zwicker's study, the stimulus was presented continuously. In the present study, however, the stimulus was gated. The expected difference in thresholds for gated and continuously presented stimuli is 5-10 dB (Green and Nguyen, 1988). The expected threshold values for gated stimuli would correspond to depths of modulation ranging from 10 to 18%. Thus in two of our conditions, the modulation depth was above the threshold for detection and the envelope fluctuations should have been clearly audible. In 10% modulation depth condition, the modulation depth was at or near threshold.

Reducing the depth of modulation results in a decrease in the amplitudes of the sidebands. The level of each sideband relative to the carrier is,

$$S_L = 20 \log m/2, \qquad (5.2)$$

where S_L is the level of the sideband relative to the carrier in dB and m is the depth of modulation. In this condition m equaled 1.0, 0.32, and 0.10 at a modulation depth of 100, 31.6, and 10%, respectively. Thus the level of the sidebands ranged from -6 (100% modulation) to -26 (10% modulation) dB below the level of the carrier tone.

At the slower rates of modulation, the temporal cue would not be as prominent due to a decrease in the sidebands' amplitudes. Because the fluctuations would still be audible, however, it was expected that performance would be quite similar across the different modulation depths. At the faster modulation rates, discrimination based on spectral cues would presumably be more difficult. The detection of a change in sideband frequency would be more difficult due to masking by the carrier tone. Thus, at the faster rates of modulation it was expected that the largest differences in the 3 modulation conditions would be seen.

<u>Results and discussion</u>

Figure 5-5 shows thresholds, averaged across listeners, for each modulation depth as a function of standard modulation frequency. In general, performance becomes poorer as the depth of modulation is reduced from 100% to 10%. There is a greater difference in the conditions at the slower modulation rates than was expected. Poorer performance for the 10% modulation depth, however, was probably due to the poorer modulation

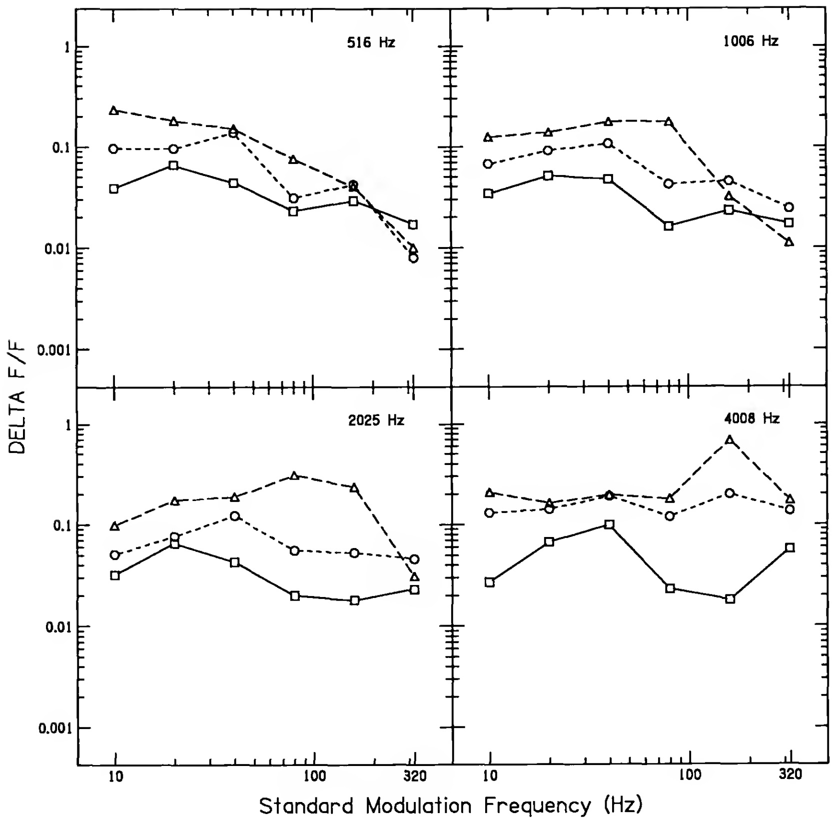


Figure 5-5. Thresholds averaged across three listeners for each carrier frequency are presented as a function of the standard modulation frequency. Three modulation depth conditions are shown: 100% (squares), 32% (circles) and 10% (triangles).

detection threshold for gated stimuli. There are some of the expected differences between the conditions at the faster rates of modulation. There is, however, an unexpected convergence of the data, especially for the 516 and 1006 Hz carriers, that is difficult to explain. Essentially the data are parallel for each carrier frequency. This suggests that the differences between modulation depths are not dependent on the carrier frequency.

Summary and Conclusions

In this study, we investigated the listener's ability to discriminate a change in amplitude-modulation rate. First, we considered the effect of carrier frequency. We determined listeners' thresholds for a fixed carrier condition for four carrier frequencies. The pattern of results was similar across carrier frequency. At the slower modulation rates, thresholds were relatively constant or slightly increased with increased modulation rate. Thresholds for the faster modulation rates were slightly lower (better performance) than the thresholds for the slower modulation rates. From these data, we conclude that carrier frequency has little or no effect on listeners' abilities to discriminate a change in modulation rate. In addition, it appears that when the carrier is fixed in frequency, modulation rate discrimination is better at the faster modulation rates.

Second, we compared three carrier conditions, fixed, random and harmonic, that provided different spectral cues. At the slower modulation rates, where discrimination is best understood in terms of a temporal process, we found little or no difference between the three conditions. At the faster modulation rates, where discrimination is best understood in terms of a spectral process, we found that thresholds in the random condition were consistently the poorest. Performance in the fixed condition was better than performance in the harmonic condition for 80 and 160 Hz modulation rates. At the 320 Hz rate, performance in the harmonic condition exceeded performance in the fixed condition. From these data, we conclude that an absolute comparison between the sideband frequencies in the two trial intervals (fixed carrier condition) provided the most likely cue for discrimination. In addition, when a sideband comparison was not possible, but pitch was a reliable cue (harmonic carrier condition), performance was better than when neither cue was available (random carrier condition).

Third and finally, we investigated the effect of modulation depth on modulation rate discrimination. We found that in general, thresholds decreased (poorer performance) with a decrease in modulation depth from 100 to 10%.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The purpose of these studies has been to further the investigation and knowledge of how listeners process complex auditory information. Two theoretical views of how listeners detect the presence of a signal within a complex waveform were presented in the Introduction. The primary differences in these views were discussed. The role energy outside the signal's critical band plays in signal detection was considered. How signal detection would be carried out in a 2AFC paradigm was described for each view. The aim of the studies in this dissertation was not to decide which of these two views was correct. Rather, in these studies we investigated various complex auditory processing tasks in light of these two viewpoints.

A second issue was the distinction between temporal and spectral processing. When listeners relied on the fluctuation rate of a waveform's envelope, we referred to that as temporal processing. When listeners relied on the frequency composition of the waveform, we referred to that as spectral processing.

We investigated the effect of signal frequency uncertainty on the detectability of a tone in two masking

tasks and presented those results in Chapter 2. The first task was referred to as the profile task. Studies have shown that profile analysis relies on across-frequency comparisons.

The second task was referred to as the noise task. Historically, the detection of a tone in noise has been described in terms of the traditional view of signal detection (Fletcher, 1940; Weber, 1978). Recently, it has been described in terms of the more recent view of signal detection (Gilkey, 1987; Gilkey and Robinson, 1986; Green, 1988; Kidd et al., 1987).

In this study, the possibility of listeners using the level in one critical band was reduced by selecting the stimulus level randomly for each presentation. Thus, for both tasks, listeners most likely had to rely on across-frequency comparisons to detect the signal. In the case of profile analysis, this would be the expected strategy. For the noise task, this would be the expected strategy if the more recent view is accurate.

Data from this study suggest that for both tasks uncertainty about signal frequency hinders detection. All listeners were better able to detect the signal if they heard a tone of the same frequency prior to the trials. This effect of signal uncertainty, however, was small for both tasks.

For the profile analysis task, the small uncertainty effect was not surprising. If an across-frequency

processing strategy facilitates the detection of an unknown signal frequency, the uncertainty effect would be minimized. These results seem to suggest that listeners were able to employ an across-frequency comparison strategy on the noise task as well. These data provide support for the more recent, across-frequency comparison view of how a signal in noise is detected. A direct comparison between the size of the uncertainty effect (in dB) for each task is difficult because the underlying psychometric functions for the two tasks are different (Raney, Richards, Onsan, and Green, 1989).

The effects of signal uncertainty slightly reduced performance in both the profile and noise tasks. In contrast, recent studies (Neff and Green, 1987; Spiegel et al., 1981) have shown that masker uncertainty produces large reductions in performance. Specifically, when a listener is trying to detect a known signal, uncertainty about the frequencies of the nonsignal tones impairs performance. These studies have provided additional evidence for across-frequency auditory processing.

We described a study in Chapter 3 that extended previous work on masker uncertainty. Rather than asking listeners to detect the presence of a signal, we asked listeners to detect an attribute of the signal, amplitude modulation. Unlike previous studies, the signal was always clearly present. The issue was whether listeners could detect changes in the amplitude of the signal.

A second issue of this work was the type of masking that occurred. We distinguished between central and peripheral masking and attempted to determine the relative contributions of each. Our results indicated that the 100-Hz modulation rate was more susceptible to both central and peripheral masking than the 10-Hz modulation rate. These masking differences between the two modulation rates were particularly clear for the 10-tone maskers.

Our explanation of these differences in masking was based on the distinction between temporal and spectral detection processes. The detection of 10- and 100-Hz modulation was described in terms of temporal and spectral information, respectively. In this study, the masker tones could be spaced no closer than a critical band apart. Thus, the analysis of the maskers would have been in terms of the frequencies of the tones composing them. Therefore, the maskers provided primarily spectral information.

The 100-Hz modulation rate may have been more susceptible to masking due to interference between the detection process of the signal (i.e., spectral) and the analysis of the masker (i.e., spectral). In contrast, less masking in 10-Hz condition could have been due to less processing interference between the signal and masker.

Similar evidence of interference between detection processes was provided recently by Yost and Sheft (1989). They found that the threshold for amplitude-modulation detection was increased (poorer performance) when an amplitude-modulated masker tone was presented simultaneously with the modulated signal. In their study, both the signal and masker carrier tones were separated by 2 octaves. It was, therefore, unlikely that peripheral masking was the basis of the across-frequency interference. Both the signal and masker carrier tones were modulated at a rate of 10 Hz, thus the interference could have been due to competition between temporal information or the envelopes of the two waveforms. Again, these data provided evidence that listeners are unable to ignore information at a distant frequency.

Our primary question in Chapter 4 was whether across-frequency interference occurred for another type of signal and masker waveform. We employed a two-tone waveform. The envelope of this signal fluctuates over time like the envelope of an amplitude-modulated tone. The results supported the Yost and Sheft (1989) findings of across-frequency interference.

A second question we considered was whether or not this interference would occur when the rate of envelope modulation was increased for both the signal and masker. We found that even at a fast modulation rate of 160 Hz interference occurred. This result suggests that the

basis of the interference was not limited to competition between temporal information at slower modulation rates.

Another minor concern was the frequency relation between the signal and masker. Yost and Sheft (1989) used frequencies that were multiples of each other. We used frequencies that were not multiples of each other and had approximately the same frequency separation they used. Again, we found the occurrence of interference between the signal and masker.

Finally, we wanted to determine if across-frequency interference would occur when the signal and masker were modulated at different rates. The modulation rate of the signal was fixed across trial blocks and we varied the modulation rate of the masker. We expected the amount of interference to decrease as the masker modulation rate was increased. This expectation was supported when the modulation rate of the masker was greater than twice the rate of the signal. This finding suggests that interference occurred even when the temporal information provided by the signal and masker are different.

The study we presented in Chapter 5 investigated listeners' abilities to discriminate an across-interval change in a signal. We presented listeners with two amplitude-modulated tones sequentially and asked them to indicate which one had the slower modulation rate. Our interest was in determining how well listeners could compare temporal and spectral information presented across

trial intervals. We focused on three questions related to modulation rate discrimination ability.

First, we investigated what effect carrier frequency had on rate discrimination. In this condition, listeners compared the same carrier frequency modulated at different rates in the two intervals. The pattern of results was similar across the four carrier frequencies. We concluded that the frequency of the carrier tone had little or no effect on listeners' abilities to discriminate changes in modulation rate.

Second, we completed a condition in which the spectral cue available to the listener was varied. At the slower modulation rates, where listeners were expected to rely on temporal cues, there was little or no difference between the conditions. At the faster modulation rates, where listeners were expected to rely on spectral cues, there were differences between the conditions. Listeners performed best when the same carrier frequency was used in each interval. We concluded that the most likely discrimination cue was a comparison between the absolute frequencies of the sidebands. These data also indicated that pitch could be used as a cue for modulation rate discrimination.

Third and finally, we investigated the effect of modulation depth on listeners' abilities to discriminate modulation rate. In general, we found that performance was poorer as the modulation depth was reduced. At the

faster modulation rates, poorer performance was expected because a decrease in modulation depth resulted in a decrease in the amplitudes of the sidebands. At the slower rates, we found a greater difference than was expected.

In closing, these studies have provided evidence that listener's signal detection strategy is not limited, at any one time, to a narrow range of the frequency spectrum. Instead, listeners appear to be able to monitor information across the frequency spectrum. There appear to be cases, however, when additional frequency information may impair performance. If the additional information is uncertain, then listeners appear to be unable to ignore it and performance is hindered. If there is similarity between the nonsignal information and the signal information (i.e., temporal or spectral), then interference and poorer performance may result. In contrast, if listeners are asked to make across-interval comparisons, then they perform well on both temporal and spectral discriminations.

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BIOGRAPHICAL SKETCH

Jill Johnson Raney, a native Floridian, began her college years at Pensacola Junior College, where she received an Associate of Arts degree in computer science in 1980. After deciding to pursue a bachelor's degree in psychology, she attended Florida State University and the University of West Florida. While working on her bachelor's degree, Jill developed an interest in research and set her academic goal for a Ph.D. in psychology. Jill received her bachelor's and master's degrees from the University of West Florida in 1983 and 1987, respectively. Jill was married in the spring of 1986 to Gary Raney, also a graduate student in the psychology program at UWF. Both having aspirations of doctoral degrees in psychology, they entered the psychology doctoral program at the University of Florida. At the time of this writing, they both anticipate graduating with doctoral degrees this year. They are eager to begin careers that combine teaching and research.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

David M. Green
Graduate Research Professor
of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Ira S. Fischler
Professor of Psychology

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Keith D. White
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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This dissertation was submitted to the Graduate Faculty of the Department of Psychology in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May, 1990

Dean, Graduate School